Investigations Into Coordinated Control of TCSC Controlled Double Circuit Line

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CERTIFICATE

It is to certify that this M. Tech thesis work entitled Investigations Into Coordinated Control of TCSC Controlled Double Circuit Line *has been carried out by* **P. Sricharan** *under our supervision and has not been submitted elsewhere for a degree.*

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Abstract

In case of regulated transmission lines, which have controllers to regulate voltage, power flow, angle across line etc, if their operation is independent of operation of other surrounding controllers then their combined operation can lead to undesirable and even disastrous results without proper co-ordination. In order to increase the power transfer capability of transmission lines and to have control on line power flows, Thyristor Controlled Series Compensators (TCSCs) are used. There is hardly any work reported in the literature about coordination of TCSC and other Flexible AC Transmission System (FACTS) controllers. In the future, when the use of FACTS devices becomes widespread, the control coordination problem is expected to emerge as one of the major problems in the operation of such systems.

This thesis studies the coordination problem for a double-circuit line with TCSC on both lines. One of the TCSCs is used for controlling power flow on its line and the other is used to control the power angle across the lines. This scheme not only co-ordinates the operation of two controllers but also improves the transient stability of the system. Even under transient fault conditions, the angle across the lines is not allowed to depart much from the set value. Under steady state conditions, the changes made in power order of power controlling TCSC will not bring in any oscillations either on the lines or in the generator because of second controller. These aspects have been investigated and observed in a single machine infinite bus system connected by a double circuit line having TCSCs on both the lines.

Simulation for step changes in power order of power setting controller and faults at receiving end of transmission line has been done using PSCAD/EMTDC package. It has been observed that in fault cases, there has been a tremendous improvement in transient stability of the system. And in case of step change in power order, with controllers on both the lines, there are no transients in generator power and the transients in line flows also die down quickly.

Thus, not only is control over power flow achieved, but also significant improvement in transient stability is obtained.

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Chapter 1

Introduction

With increasing load demand on modern complex power systems, there is a need for enhancement of power transfer capability of transmission lines. In practice ac transmission lines, particularly long lines, are under-utilized.

1.1 Limitations to Power flow

Limitation to power flow is mainly because of the following reasons:

- Unsatisfactory voltage profile with increased power flows.
- Inadequate stability margin with increased power flows.
- Inadequate compensation of line series impedance and shunt admittance.
- Furthermore there may be problem with forcing of power to flow along desired paths because of existance of other paths over which power may flow in preference to the desired path. This is commonly termed the Loop Flow Problem. The problem of loop flow may be compounded by changing network topology following contingencies.

The power flow over an ac line between two buses 1 and 2 is given by the following approximate formula

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{1.1}$$

where

P is the line power flow,

V_1 and V_2 are voltage magnitudes at the buses connected by the line,

X is the total series reactance of the line and

δ is the phase angle difference between the two bus voltages.

1.1.1 Large Reactance

Long lines will have large series reactance. This reduces the power transfer through the line, as from the earlier equation power transfer is inversely proportional to the reactance of line. By reducing this line reactance using series capacitors, one can increase the maximum power transfer capability of the line.

1.1.2 Voltage Limits

The bus voltages are usually stipulated to be within $\pm 5\%$ of the nominal voltage. Thus, bus voltage magnitude variation cannot be resorted to control power flow.

1.1.3 Stability

Transient stability describes the ability of a power system to retain synchronism following major disturbances. In order to have a good transient stability margin, it is recommended that the angle difference between the buses should not exceed 30^o in steady state. So, this limits the actual power flow through the line to half the maximum power transfer capability.

1.1.4 Loop flows

Loop flows are those flows which are an unwanted result of the operation of the overall interconnected transmission grid, where the circuit laws dictate power flow paths in conflict with the desires of one or more of the parties involved in using the transmission system. These flows are of concern primarily in the steady state, where the undesirable loading of certain lines and underloading of certain other lines become matters of concern. The effects may be on voltage levels, losses, reduction of thermal or stability margins needed for secure

operation. These flow problems are addressed in conventional systems by using either phase shifting transformers or series compensators. The series compensation can be capacitive to increase power flow or inductive to reduce power flow in a particular line. Power electronic controllers can also achieve each of these functions. Speed of operation however is not a major concern in this load flow problem, so such controllers will be justified only if vernier control or frequent adjustments are required.

1.1.5 Thermal limits

Thermal limits are inherent in transmission systems, due to both conductor limits and series equipment such as transformers, reactors, or series capacitors. Transmission lines are generally operated well below the thermal limits to provide security in the event of a major disturbance. The role of controllers will be to affect the operation of the system, usually in response to the disturbances of concern, to permit improved utilization of this inherent thermal capacity.

A major focus of present research in power systems is on means to achieve increased power flows along desired paths while observing various constraints without major changes in the system. As the existing lines are usually under-utilized, it is desired to increase their power transfer capability. Traditionally it was not possible to control power flow over a line in a network. This is the reason why ac lines are called uncontrolled lines as far as power transfer is concerned. However, control can be achieved through series compensation which changes the effective series reactance of the line. This compensation is of two types, fixed and variable. Fixed compensation has some disadvantages. For example if the level of series compensation is high then, the interaction between the torques generated by the resonant currents and the torsional vibrations of turbine-generator units results in a phenomenon called Sub Synchronous Resonance (SSR). If the damping for these modes of vibration is not high, it may result in shaft breakage. Under such circumstances, series capacitors have to be bypassed. Fixed compensation cannot give flexibile control over power transfer. Therefore variable series compensation is suggested. Variable compensation with capacity for fast variation can be used for the auxiliary purpose of suppressing SSR also.

In transmission systems with multiple parallel paths between generation and load, the actual major power paths can have an important impact on system operation during both steady-state and post-contingency conditions. It is anticipated that power electronic con-

trollers will be used widely in the future to control power flow along desired paths in such cicumstances. By employing variable series compensation using power electronic controllers, power flow over an ac transmission line becomes flexible. In otherwords, such an ac transmission system becomes a flexible ac transmission system (FACTS).

1.2 FACTS

The IEEE definition for FACTS [1] is as follows: " Alternating current transmission systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability". This collective acronym FACTS has been used in recent years to describe a wide range of controllers, many of them incorporating large power electronic converters, which may, at present or in the future, be used to increase the flexibility of power systems and thus make them more controllable. Some of these controllers are well established and some still in the research or development stage. Research institutions, utilities and manufacturers throughout the world are pursuing R&D programs in FACTS with the following two main objectives:

- To increase the power transfer capability of transmission networks, and
- To provide direct control of power flow over designated transmission routes.

These objectives have been addressed by electric utilities over their entire history. Generally, in the past, adding generation and transmission in judicious locations provided most of the desired capability to meet the increasing demand. In recent times, it has become difficult to build additional transmission lines because of economic and environmental reasons. This has necessitated examination of strategies for better utilization of existing transmission system. Modern power electronic compensating and controlling systems are seen to be the means to achieve this goal. It is this aspect which is the focus of FACTS controller development.

High voltage DC transmission and Static Var Compensators are examples of power electronic systems which are already well established. There exist other ways to configure power electronic FACTS components to aid ac power transmission. The FACTS controllers are of two types: shunt connected controllers and series connected controllers.

1.2.1 Shunt controllers

Shunt controllers are used to provide reactive power compensation to control voltages at desired buses [2] . Depending on location of these shunt controllers, reactive power compensation brings in significant enhancement in active power flow also. There are different types of shunt controllers as described below.

Static Var Compensator (SVC)

Before static var compensators became widely available, the adjustment of voltage in a transmission system, other than at the terminals of a generator, was possible only by mechanical switching of shunt elements or by providing synchronous condensers. The switching of shunt reactors or capacitors is comparatively crude, causing abrupt voltage changes along with voltage and current transients. The SVC on the other hand provides rapid and fine control of voltage without moving parts. These have been available in various forms and have been in use since the early 1960s. Earlier technologies included the saturated reactor which is not a power electronic system , but since 1980s the thyristor has been the sole basis for shunt var compensating equipment.

The SVC uses conventional thyristors to achieve fast control of shunt connected capacitors and reactors. The elements of controller consists of:

- A fixed capacitor (FC) which provides a permanently connected source of reactive power, designed also to act as a harmonic filter.
- A thyristor controlled reactor (TCR) which consists of bi-directional thyristor valves in series with shunt reactors, usually in a delta configuration. These thyristors may be switched at any point over the half wave (90^o to 180^o electrical behind the voltage wave) to provide fully adjustable control over the full range of rated reactive power absorption. Harmonic currents are generated at any angle other than 90^o (full conduction) and 180^o (zero conduction).
- The thyristor switched reactor (TSR) has the same equipment as a TCR, but is used only at fixed angles of 90^o or 180^o. It is either fully on or fully off and thus generates no harmonics.

The SVC helps to overcome the typical transmission problem of falling voltages with increasing loads. When a parallel line is removed due to a fault, the remaining line may become heavily loaded, reaching the lower practical limit of steady-state voltage. The compensator provides reactive power support for this condition to quickly restore the voltage and quickly removes it should load be removed. It is possible with an SVC not only to maintain a reference voltage level, but also to modulate the reference voltage signal in order to improve system damping. Such controls use auxiliary control signals to modulate the voltage level in accordance with the rate of change of phase angle or power flow.

Static Synchronous Compensator (STATCOM)

The STATCOM, previously refered to as Static Synchronous Condenser (STATCON), resembles in many aspects of its characteristics a rotating machine used for reactive power compensation. It behaves as a solid state synchronous voltage source that is analogous to an ideal synchronous machine which generates a balanced set of sinusoidal voltages, at the fundamental frequency, with rapidly controllable magnitude and phase angle. Typical applications of this STATCOM are same as those of SVC: voltage support and prevention of voltage collapse, transient stability improvement and power oscillation damping. It is surmised that in addition to reactive power compensation, with a suitable DC energy storage device such as a battery or super conducting magnet, this controller might in the future be used to handle peak power demand and prevent power interruptions.

Thyristor Controlled Braking Resistor (Dynamic Brake)

Conventional braking resistors have, in the past, been used with generators as a means of controlling potentially destabilizing system disturbances. Braking resistors are designed to provide generator speed control by dissipating power in a power resistor. Stability limits of synchronous generators can be improved by reducing the imbalance between machine mechanical power and electrical power during system faults. Thyristor controlled braking resistor can enhance the above function by using electronic rather than mechanical switching. This will give a faster response in both closing and reopening Also electronic switching will enable braking resistors to provide a dynamic response, for example, in only applying damping on the positive cycle of machine swinging. Electronic switching will also enable the additional benefit of providing a variable amount of braking resistance for improved damping

control.

1.2.2 Series Controllers

These controllers are used for active power flow control. They are connected in series. The different types of series controllers are:

Thyristor Controlled Phase Shifting Transformers

The basic function of a phase-shifter is to provide a means to control power flow in a transmission line. Historically, this has been accomplished by specially connected mechanical regulating transformers. Because the power flow on transmission line is proportional to sine of the angle across the line, the steady-state power flow can be controlled by utilizing a phase-shifter to vary the angle across the line. Just as traditional phase shifters can be employed to alter the steady-state power flow, they can be used to alter transient power flow during system disturbances or outages, if the phase shifter angle can be changed rapidly. Rapid phase angle control can be accomplished by replacing the mechanical tap changer by a thyristor switching network.

The potential benefits of transient alteration of power flow by high speed phase shifter include:

- Damping of system oscillation.
- Mitigation of transient or post-disturbance voltage dips due to heavy line loading.
- The control of line flows and mitigation of the problem of heavy through-flows which might cause cascading relay action leading to loss of synchronism or might lead to abnormal reactive power consumption.

Thyristor Controlled Series Compensator

Power transfer between two buses can also be controlled by adjusting the net series impedance of the line. One such established method of increasing transmission line capability is to install a series capacitor which reduces the net series impedance, thus allowing additional power to be scheduled. This method of series compensation is well known. Conventional

series compensation schemes switch capacitors to vary the level of compensation using mechanical devices such as power circuit breakers. The limitations of mechanical switching devices force conventional series compensation schemes to be switched in relatively large discrete segments. Furthermore, the scheme is slow in terms of response time. Thyristor controllers have the capability of rapid control of line compensation over a continuous range with resulting flexibility.

Controllers used for series compensation have to date been developed in two different configurations: Thyristor Controlled Series Compensator (TCSC) and Thyristor Switched Series Compensator (TSSC). TCSC controllers use Thyristor Controlled Reactor (TCR) in parallel with capacitor segments. This combination allows capacitive reactance to be controlled smoothly over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously resulting in insertion of an inductive reactance into the line. In some applications a smooth control of reactance will be needed to securely damp power swings or to regulate power flow on adjacent paths. TCSCs also allow higher levels of series compensation with significantly reduced risk of SSR interaction [3] . Operated in a vernier mode they take on an inductive-resistive impedance characteristic at SSR frequencies, thus acting to damp those oscillations. TSCSs can be quickly switched to "bypass" mode (within 1/2 cycle) with the resulting inductive reactance effective in reducing short-circuit current levels. When conventional series capacitors are inserted in a line, a DC offset exists in the capacitor voltage which dissipates slowly as a subsynchronous oscillation. With a TCSC, this post-insertion DC offset can be eliminated within a few cycles by active control of bi-directional thyristors. TCSC and TSSC controllers can be used to quickly bypass the series capacitors for protection from fault induced over voltages and to rapidly reinsert the capacitors after fault clearing to improve system recovery following network disturbances. The resulting protective action allows reduced metal oxide varistor (MOV) energy ratings with thyristor controlled schemes. TCSCs are also used for damping of small signal power oscillations in a tie-line [4]. Analog simulator studies have been done in effectiveness of TCSC in enhancing dynamic stability [5]. Strategies for power oscillation damping with TCSC using local parameters, is also reported in literature .

1.3 HVDC Transmission

High Voltage Direct Current (HVDC)Transmission is also used for transmitting large amounts of power over long distances. Furthermore, it is used for connecting asynchronous systems or for long overhead or submarine connections where it proves more economical than an ac connection. It is possible to interconnect systems of different nominal frequencies as well as those with the same nominal frequency using a dc link without any change in operating frequency policy by either system. The markable advantage of HVDC controls over FACTS is the absolute control of power flow. Control of power flow in HVDC transmission is achieved by the timing of valve firing; adjusting one end (usually the inverter) to maintain a constant voltage independent of current, and the other end (usually the rectifier) to control the current. Another advantage of HVDC is that it does not add to the short-circuit level of ac system, as for faults on DC line, valve controls operate in such a manner that fault current is almost zero or equal to the current margin.

DC control operations can be made to provide modulation of DC power in response to deviations in system frequency, generator rotation speed, busbar voltage angle etc, regardless of the types of systems interconnected in such a way as to result in improvement of power system stability and damping of electromechanical oscillations.

1.4 Motivation

The main objective of either series compensating FACTS controllers or HVDC controllers is to achieve control over power flow on transmission lines. These controllers dictate setting of power flow on their respective lines. But then, neither HVDC links nor these series compensated lines are independent by themselves, but are integral parts of a system that consists of several such regulated and unregulated lines. If the control of power flow on their lines is the only criterion of these controllers, then the effects of control changes made on these lines will be felt on other lines, which is undesirable. Therefore, the behaviour of these controllers should not be "selfish" causing undesirable effects in other lines. In case of an environment consisting of several such controllers, they have to interact among themselves [6] properly for satisfactory overall operation. Their interaction, if not coordinated properly may even lead to disaster. Chances for control conflicts are more likely in case of such controllers operating in parallel. What that is desired from such controllers is to achieve

flexible control on power flow through transmission lines in a desired route, minimize network transients following a disturbance and at the same time avoid control conflict among them. Not much work has been reported in literature about possible conflicting interaction of such controllers and the need for their coordinated operation. Bhat [7], has made a study into the control strategies of variable series compensators in a double circuit line. But, then his control strategy does not eliminate this conflict and moreover his controller does not work satisfactorily for transient fault case, as was seen in a PSCAD simulation. This has motivated a fresh examination into the control strategy of TCSCs in a double circuit line connecting a single generator to an infinite bus.

1.5 Brief Overview of Thesis

Series compensation is employed to increase power transfer capability of transmission lines. For, fixed series compensation schemes, SSR poses a serious limitation to the level of series compensation [3]. Hence, variable series compensation, such as TCSC is employed to effectively increase the power flow through transmission lines to their natural load or even higher than that. In case of several such TCSCs operating in parallel, there is a need for coordinating their controls. An investigation has been made in this thesis into the coordinated operation of TCSCs in a double circuit line connecting single generator to infinite bus. In order to avoid control conflict between these two TCSCs, one of them is made to control power on its line and the other one is assigned the job of controlling power angle across the lines. For this configuration, a novel control strategy has been developed and various cases have been studied through PSCAD simulation. The strategy makes the power controlling TCSC to implement changes in its power reference, without any oscillations on either of the lines as well as in generator. This has been simulated in PSCAD for 100MW of step change in power reference. The strategy offers another markable advantage of tremendous improvement in transient stability of the system. Without these controllers, for a 2.5 cycle three phase fault at the receiving end of one of the two lines the system loses synchronism. Whereas with angle controller on second TCSC, the system gets stabilised not only for 2.5 cycle fault but also even for a 5 cycle fault at same location.

Chapter 2

Formulation of control strategy

As seen earlier, the problem of co-ordinated control of TCSCs and/or HVDC lines operating in parallel is not trivial. Their operation should be such that the changes brought by them do not have deleterious effect on the rest of the system. There should not be conflict between the objectives of the various controllers. It may, in general, be necessary to have master controllers to coordinate the control tasks of the various controllers, though, decentralized operation is preferable if it is possible.

2.1 Problem Formulation

We will examine the operation of two parallel lines with TCSC on them. The lines are fed by a generator at the sending end and are connected to an infinite bus at the receiving end. The generator may or may not have local loads. Here we may try to operate them in such a way that the total power order of the two lines is equal to the power input of the lines. One of the TCSCs can be made the master in the sense that it sets its power order independently and simultaneously sends command for setting of power order of the other TCSC in order to make the total power order of the two lines equal to the input power. If the input power is directly the power supplied by a generator, then the total power order of the lines should match the power setting of the turbine-generator system. Otherwise there will be conflict between the generator and line power setting controllers. If the input power is not directly

obtained from generator, there is problem in determining line power orders. Permissible power order determination is not a straightforward task except in isolated cases such as an HVDC line. In general, power order determination for power setting controllers may have to be a part of the optimal load dispatch problem.

From the foregoing, it is clear that in the case of two TCSC controlled parallel lines, both lines should not be operated in the power setting mode independently. Cooperative operation of the two controllers can be secured by using one of them for power setting with the other one used for a different purpose which is not in conflict with the operation of the power setting TCSC. Power angle regulation was seen to be one such purpose. The advantage of this type of control is that power angle regulation is intuitively felt to improve transient stability of the system. The present work is a study of this type of control for TCSC controlled double circuit line.

Line angle control can be implemented by a closed loop control strategy where the reference(desired) angle is compared with the actual angle and the error in angle is utilized to change the firing angle of TCSC thyristors. However, this type of control will lead to electromechanical transients in generator with the concomitant power oscillations on the angle setting line. A damping controller will become necessary to damp out these oscillations. We will follow a different strategy here to avoid the above problem as explained below. We will endeavour to utilize only local variables for control.

2.2 Control Strategy

In the system shown in Fig 2.1,

- **G** is the generator
- $\mathbf{V}_1$ ang $\mathbf{V}_2$ are voltage magnitudes at buses 1 and 2.
- $\mathbf{P}_1$ and $\mathbf{P}_2$ are power flows through lines.

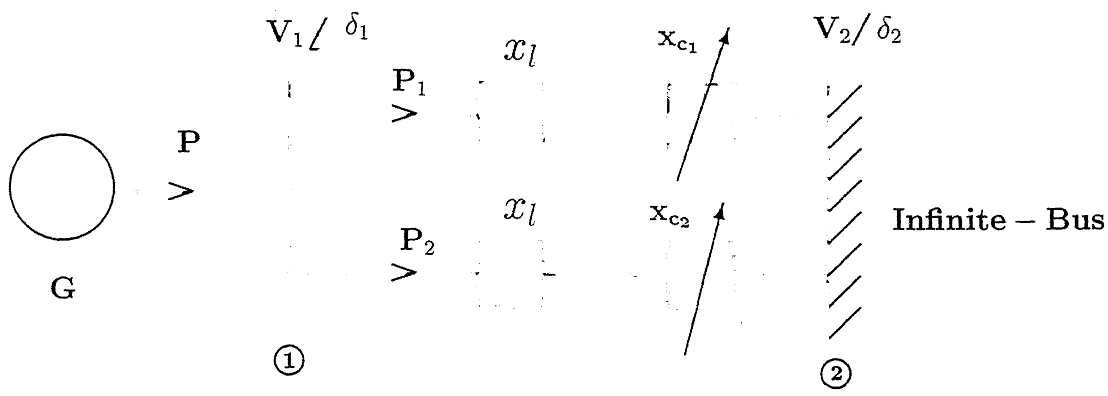

Figure 2.1: Single machine - Infinite bus system

- **P** is the power input at the common bus.
- x_l is the reactance of each line.
- X_{c_1} and X_{c_2} are reactances of TCSCs.
- δ_1 and δ_2 are phase angles of voltages at buses 1 and 2 respectively.

Let $x_l + X_{c_1} = X_1$ and $x_l + X_{c_2} = X_2$

From eqn 1.1,

$$P = \frac{K}{X} \tag{2.1}$$

where

$$K = V_1 V_2 sin\delta \tag{2.2}$$

and

$$X = \frac{X_1 X_2}{X_1 + X_2} \tag{2.3}$$

The constant **K** is determined using eqn 2.2 for the desired δ. Also, for a given P and for a given δ, X is determined from eqn 2.1

Once, K and X are determined, rest of the operation is done using local variables only. Let line 1 be the power setting line. Let $\mathbf{P}_1$ be the value of power set for this line. From

this power, X_1 is computed as

$$X_1 = \frac{K}{P_1} \tag{2.4}$$

From X_1 and X, X_2 is computed as

$$X_2 = \frac{XX_1}{X_1 - X} \tag{2.5}$$

From X_2, the reference power for second line is computed as,

$$P_2 = \frac{K}{X_2} \tag{2.6}$$

Now, the power setting of the power controller of line2 is made equal to $\mathbf{P_2}$. Initially, the effective reactance of line 1 may not be that given by eqn 2.4. The above control strategy, however is expected to force changes in $\mathbf{X_1}$ and $\mathbf{X_2}$ such that ultimately the power angle of the lines will go to the desired value with line 1 carrying the set value power.

For implementing the above control strategy, the total power **P** of the lines should be measured. What is proposed to be done is to measure the steady state value of **P** and use this value in the control as explained above. This value is updated only when the steady state changes to a new value. This is a simple measurement and can be done even locally, at the TCSC site. Under fault conditions, the control uses **P** as given by the prefault steady state.

2.3 Power Controller

The power controller is a Proportional-Integral(P-I) controller shown in Fig 2.2, where

P_{meas} is the measured power on the line.

P_{ref} is the reference setting in power.

K_p is the Gain of the Proportional Controller.

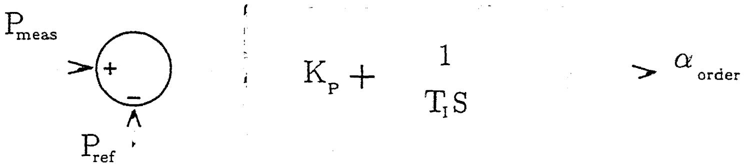

Figure 2.2: Proportional-Integral (P-I) Controller

T_I is the time constant of Integrator.

α_{order} is the firing angle order to the TCSC thyristors.

The operation of P-I controller is such that the error $\mathbf{P}_{ref}$ - $\mathbf{P}_{meas}$ goes to zero. How fast the error goes to zero depends on the rate of integration i.e. T_I. But, high values of T_I results in oscillatory response, which is not desired. Similarly, K_p should not also be too high since this may also lead to oscillatory response and firing angle hitting limits. Therefore, proper choice for these parameters should be made.

2.4 Operation of TCSC

If voltage across the capacitor of TCSC is taken as reference, then a firing angle of 90^o means

- Full conduction of thyristors.
- Inductive reactance of Thyristor Controlled Reactor(TCR) is minimum.
- TCSC will be operating in inductive mode with a minimum inductive reactance effectively.

For a firing angle of 180^o,

- Zero conduction of Thyristors.
- Inductive reactance of TCR is infinite.

- TCSC will be operating in capacitive mode with a minimum capacitive reactance effectively.

As the firing angle increases from 90°, the inductive reactance of TCR increases and also the net reactance of TCSC (inductive) increases upto resonance. Usually, resonance occurs around 120°, depending on L and C parameters of TCSC. During resonance, the impedance offered by TCSC is very high, almost infinite. After this, as firing angle increases, the net reactance offerd by TCSC becomes capacitive and it reduces with increase in firing angle and becomes minimum at 180° firing angle.

TCSC generally consists of a Thyristor Controlled Reactor(TCR) in shunt with a capacitor as in Fig 2.3. This combination is connected in series with a transmission line. By varying the inductive reactance of TCR, the net reactance of TCSC can be varied both on inductive as well as on capacitive side. In practice, TCSC is mainly operated in capacitive region only, for providing compensation to the transmission line. Some times TCSC is operated in inductive zone also, to limit the short-circuit currents. But, while operating in inductive zone thyristors of TCR are made to conduct fully (90° firing w.r.t. capacitor voltage).

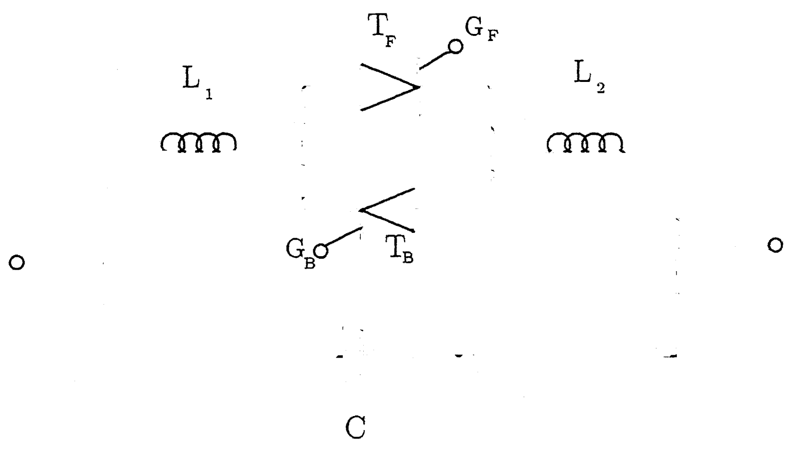

Figure 2.3: Thyristor Controlled Series Compensator (TCSC)

In Fig 2.3,

L_1 and L_2 are inductors of Thyristor controlled reactor (TCR).

C is the capacitance of TCSC.

T_F and T_B are forward and backward thyristors of TCR.

G_F and G_B are Gates of forward and backward thyristors respectively.

2.5 Operation of Controllers During Fault

Assuming there is fault on line 1, power on line 1 reduces. Now, the TCSC tries to increase power flow through that line. So, the firing angle of first controller will reduce. Furthermore, because of the fault, the power flowing in line 2 also decreases because of depressed voltages. However, the power controller of line 2 will try to bring the power level up. Because of this, even during the faulted state, power angle of the line tends to get regulated. Hence, it can be claimed that the control strategy improves the transient stability of the system in addition to enhancement of the power transfer capability of the line.

If it is desired that the controller should work for transient faults also, then care should be taken while designing L and C values of TCSC. Under transient conditions also, TCSC should be capable of operating at low values of firing angles in order to increase power flow to reduce the acceleration of the machine. L and C values have to be so chosen that at firing angles slightly above than those correspond to resonance, TCSC reactance should be sufficiently high (capacitive) to decelerate the machine.

2.6 General Criterion for Design of L and C values of TCSC

The capacitance value will be fixed depending on the level of compensation required. Then, the value of L should be chosen such that their resonant frequency will be around 2 to 2.5 times nominal frequency [8]. Also, those values should be such that the steady state operating point falls in the middle of capacitive region of operation of TCSC. The advantage of this is that during disturbances, there will be enough margin on either side.

2.7 Extremes of Operation

There will be certain situations where the operation of TCSC will reach its limits.

- TCSC will hit the limit if the power order to the power setting line is such that its order is greater than the power input at the common bus. Then, logic should be incorporated in the control such that the power flow on the line will be maximum permissible value. In this case power setting controller will hit the upper limit. This situation can arise in the case of load rejection.

- TCSC will hit the limit in case if power order to first line is given a very low-value, then, the controller of that line may hit the lower limit. On the otherhand, second controller's power order may increase to such a value that the second controller will operate at its upper limit to maintain the angle. In this case, the power controllers would essentially have lost control and the lines will behave as lines with fixed compensation.

- Too low value of power angle requirement with high total line power flows will also result in TCSCs hitting limits. Similarly, too high a value of power angle requirement with low total line power flows will result in TCSCs hitting limits.

  It is essential to coordinate specification of power angle requirement with total line power flow values in order to avoid the TCSCs hitting their limits of operation.

Chapter 3

Main Results

In this chapter, the PSCAD simulation results for various cases examined are presented. The details of system considered for study with its controls and PSCAD representations are given in the Appendix. The control strategy is as given in chapter 2. The system considered is a single machine-infinite bus system with a double circuit line. The terminal voltage of generator is 22kV. Infinite bus voltage is 230kV. Transmission line voltage is 500kV. Base MVA of the system is taken as 1110. A study, to get an idea of the power transmission capability of the line, keeping the power angle of the line at 35^o gave the following results under steady state:

- With no line compensation and no local load at generator, generator power is 1050MW.
- With 20% fixed series compensation on both lines , generator power is 1300MW without any local load.
- With TCSCs on both the lines with their controller references appropriately set, generator power is 1400MW without any local load.
- With TCSCs on both lines and with a local load of 535 MW at the generator, with same settings of TCSC controllers as in above case, generatot output is 1900MW

  It is assumed that the lines have the capacity to carry the above powers.

3.1 Results for various cases investigated

3.1.1 Case 1: TCSC on line 1; line 2 uncompensated; no local load of generator

This case demonstrates the selfish behaviour of TCSC power controller. One line has TCSC and the other line is uncompensated. Under steady state, each line carries 650MW of power. A step increase of 100MW is given to the reference order of TCSC power controller at 2.5s. From the simulation results the following are seen.

1. From Fig 3.1, power on the line that has TCSC got changed from 650MW to 750MW after a non-oscillatory transient lasting about 0.5s.

2. Because of a change in network topology, generator felt transients and there are oscillations in generator power lasting for about 4 seconds.

3. Because of the controller action, the transients are not seen on line having TCSC but, are seen on to the uncompensated line.

4. As the input power to lines is not changed, the power on the second line reduces by 100MW.

5. The oscillations in power angles of generator and the lines are shown in Fig 3.2. Fig 3.3 gives oscillations in frequency of line current.

The above result clearly demonstrates the selfish nature of TCSC power controller. Following its power order change command of line 1, the order is, realised in about 0.5s. This, resulted in reduction of power flow on the second line and also undesirable transients in the generator as well as in second line. The TCSC controller implements its command without concern for the effect of its implementation in other places in the system.

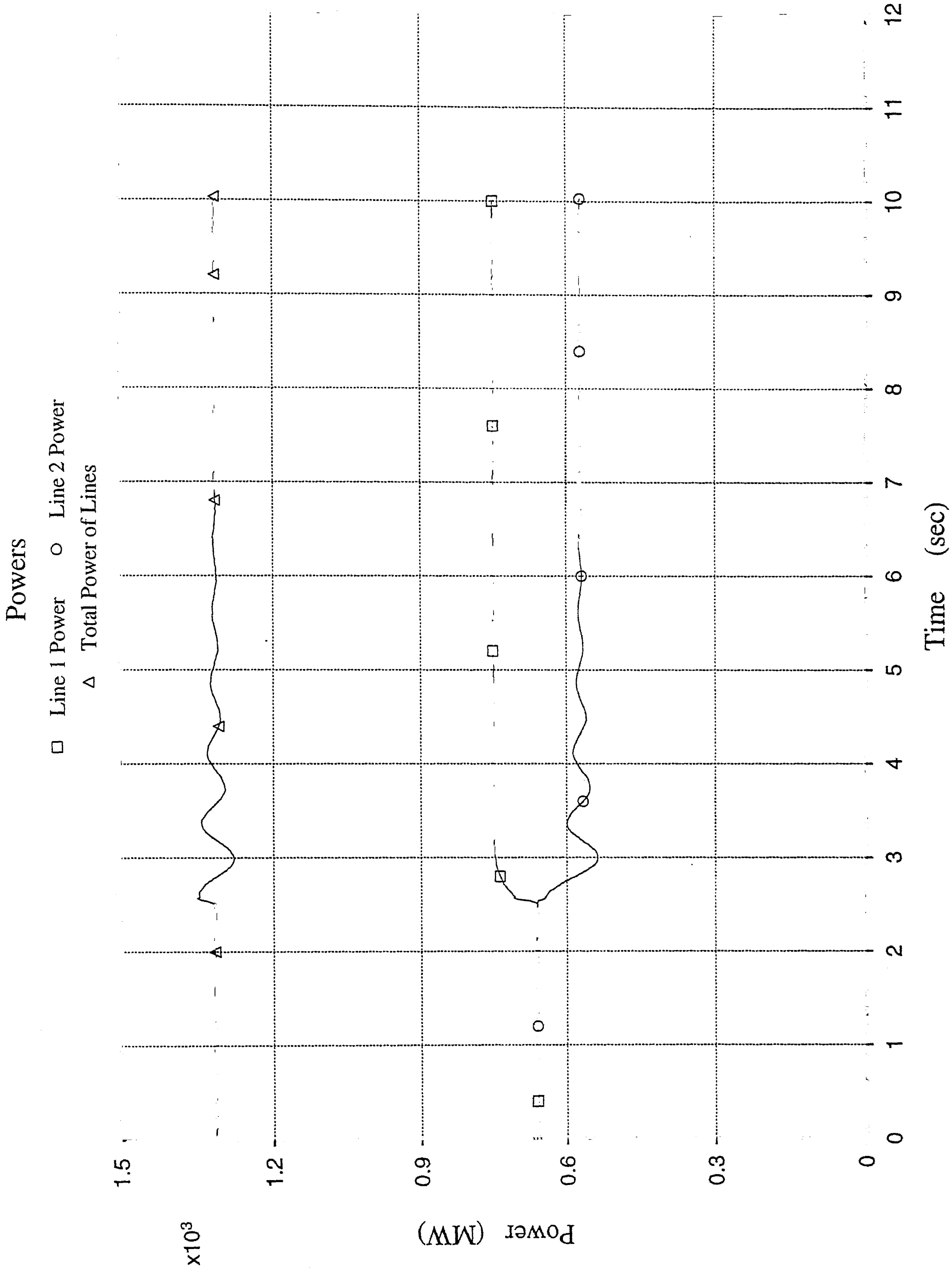

Figure 3.1: Powers: One TCSC - step change in power order

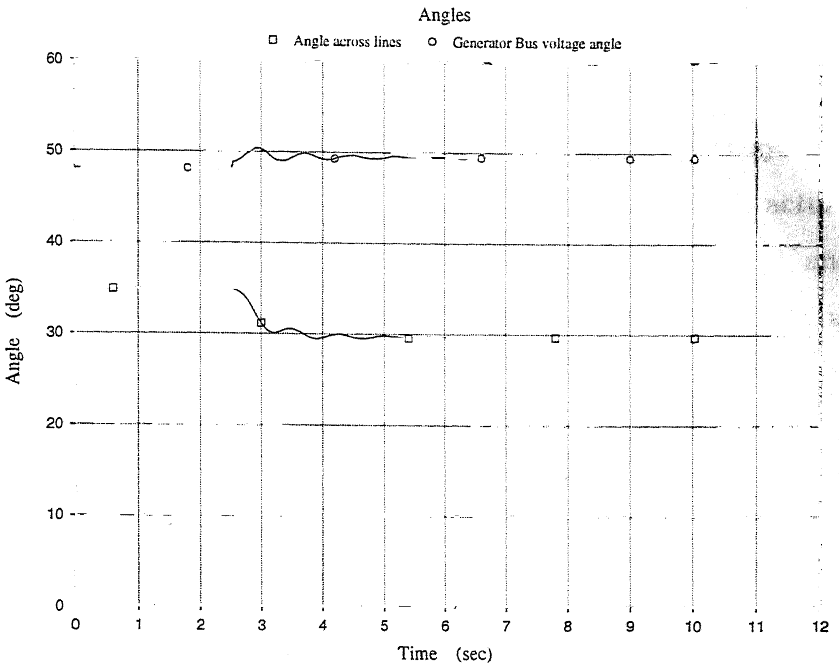

Figure 3.2: Angles: One TCSC - Step change in power order

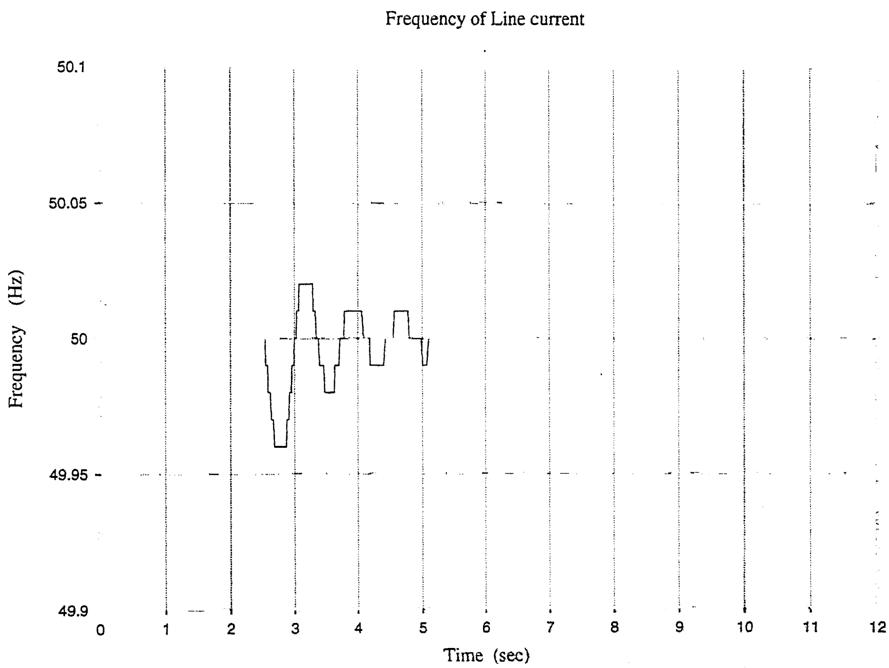

Figure 3.3: Frequency: One TCSC - Step change in power order

3.1.2 Case 2: TCSC on both lines; no local load of generator

This case demonstrates the advantage of having controller on second line whose operation is coordinated with controller on line 1 and that of turbine-governor system of generator. Here, the second line is also provided TCSC with a power controller to actually control the angle across lines as discussed in Section 2.2. Initially line 1 carries 650MW and line 2 carries 750MW. Step increase of 100MW in power order of line 1 at 2.5s. The coordinated operation of this angle controller with the power controller of line 1 results in fast implementation of the commands without transient oscillations. The following observations are made from the simulation results.

1. Fig3.4 shows the time response of power on lines 1 and 2 and total power of the two lines. The settling time is less than 0.5s so far as each line is concerned. There are no transients in total power.

2. Fig3.5 shows the generator and line angle responses. The line angle command is 35^o. The settling time for angle following step command is about 1.5s.

3. Fig3.6 gives the transient in frequency of line current.

4. Fig3.7 gives the firing angle orders of TCSC power controllers. The relative slow response of firing angle of line 2 is seen.

3.1.3 Case 3: TCSC on both lines; local load of generator present

This case is similar to case-2, additionally there is a local load of 535MW at the generator. In this case also, a step change of 100MW is given to the power reference of controller on line-1 at 2.5s without changing the line angle setting at 35^o. From figures 3.8, 3.9, 3.10, 3.11, we observe the following.

1. Power on line-1 changes from 650MW to 750MW with non-oscillatory transient lasting less than 0.5s.

2. Power on second line decreases from 750MW to 650MW with a non-oscillatory transient lasting less than 0.5s.

3. No transients are seen in generator quantities.

4. Angle across lines is maintained at 35^o after a very small magnitude departure from the set value lasting for about 1s.

Fig3.12-3.15 show responses when the line angle set point is changed from 40^o to 30^o without changing the power setting on line 1. Line flows prior to application of step change command for angle are 750MW on line 1 and 650MW on line 2 with a 535MW local load at the generator. The responses are interesting. The salient features of the responses are given below.

1. Power on line 2 as well as generator power show transients lasting for about 3s with some irregular oscillations, (Fig3.12)

2. Power on line 1 is relatively free of transient effects, (Fog3.12)

3. Line angle transient is oscillatory and the transient lasts for about 4.5s.

4. Fig3.15 shows the responses in the reactances of TCSCs on the two lines. It is seen that reactance change in line 1 takes place even with no change in reference power setting of the line. This is required for achieving the line angle change stipulated by the angle controller.

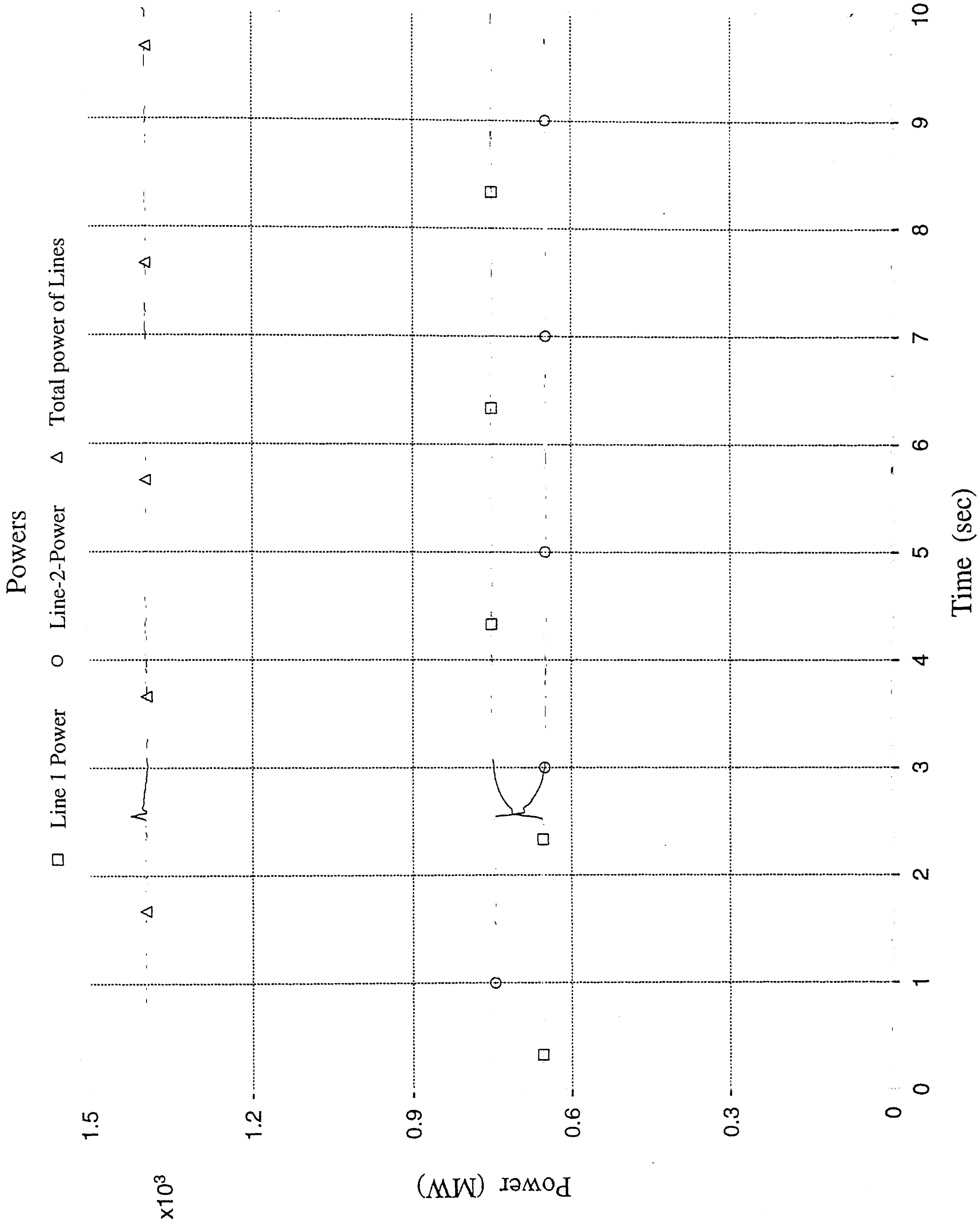

Figure 3.4: Powers: Two TCSCs - No Local load - Step change in power order

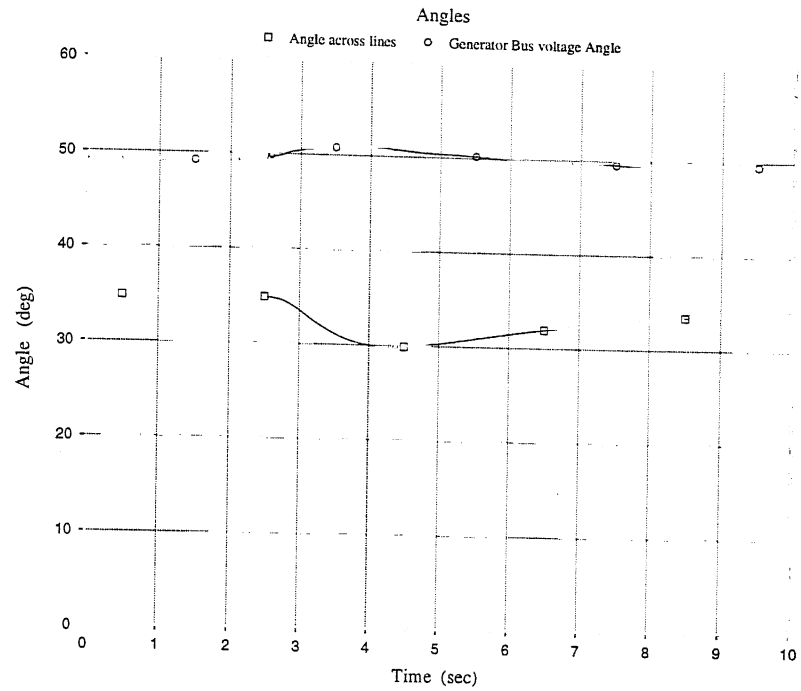

Figure 3.5: Angles: Two TCSCs - No Local load - Step change in power order

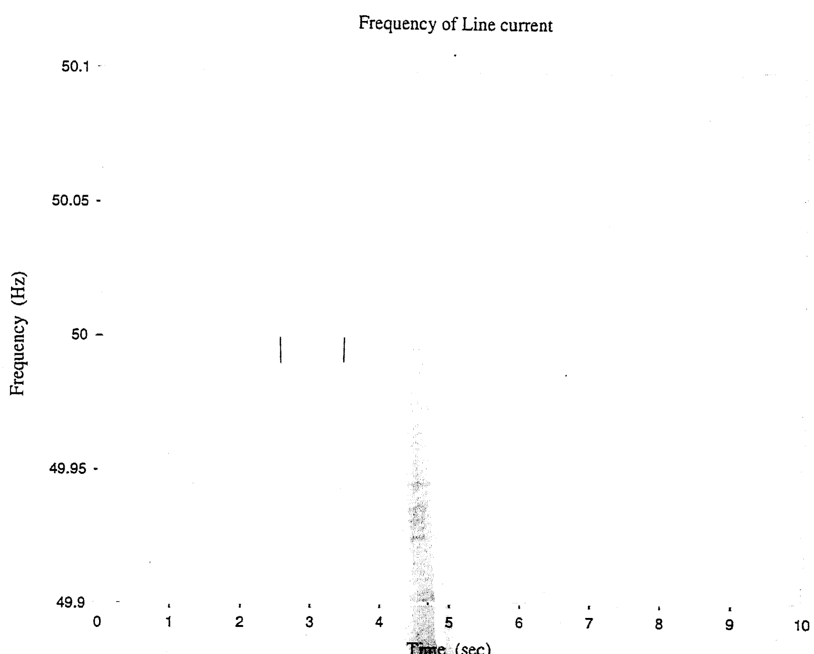

Figure 3.6: Frequency: Two TCSCs - No Local load - Step change in power order

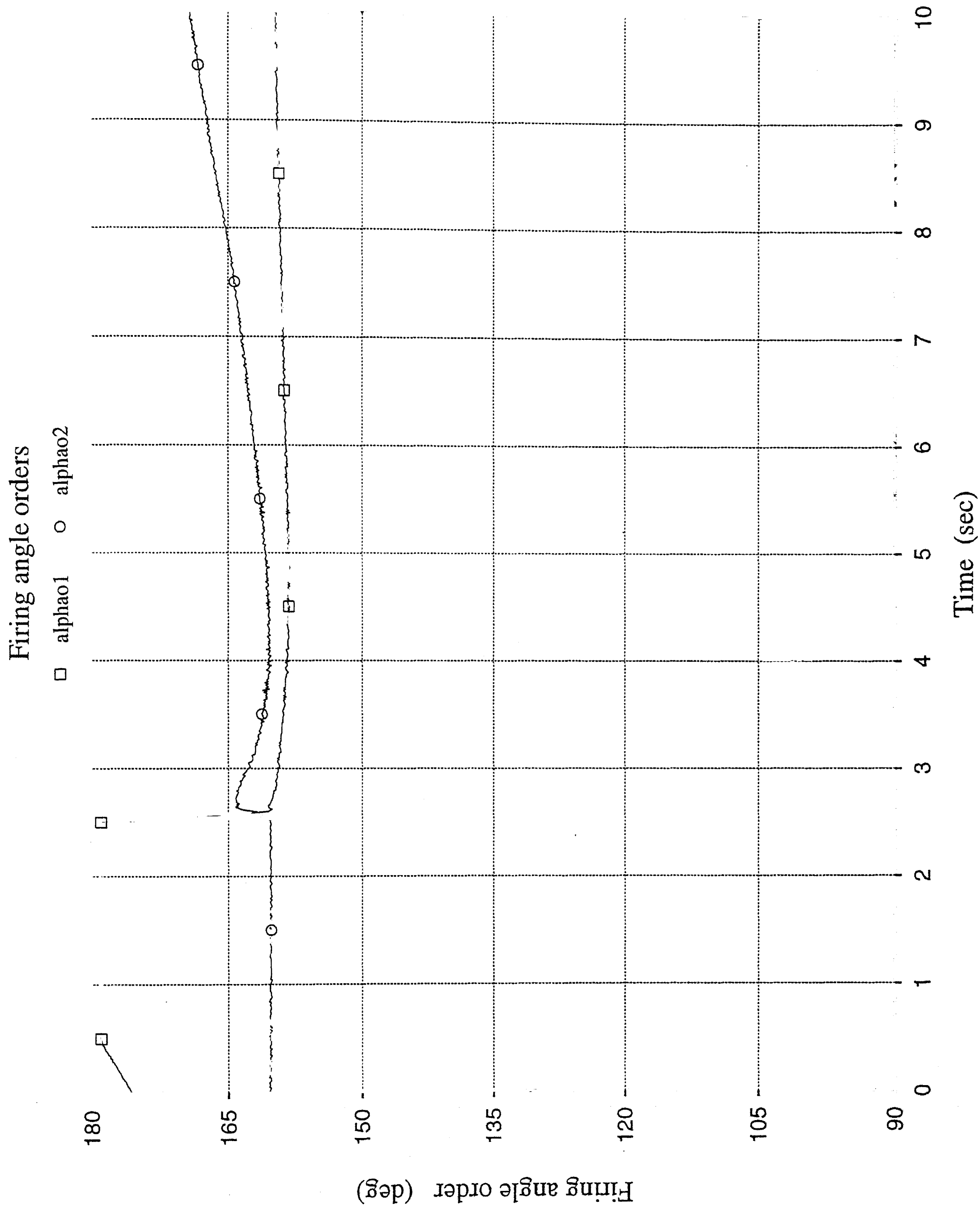

Figure 3.7: Firing Angles: Two TCSCs - No Local load - Step change in power order

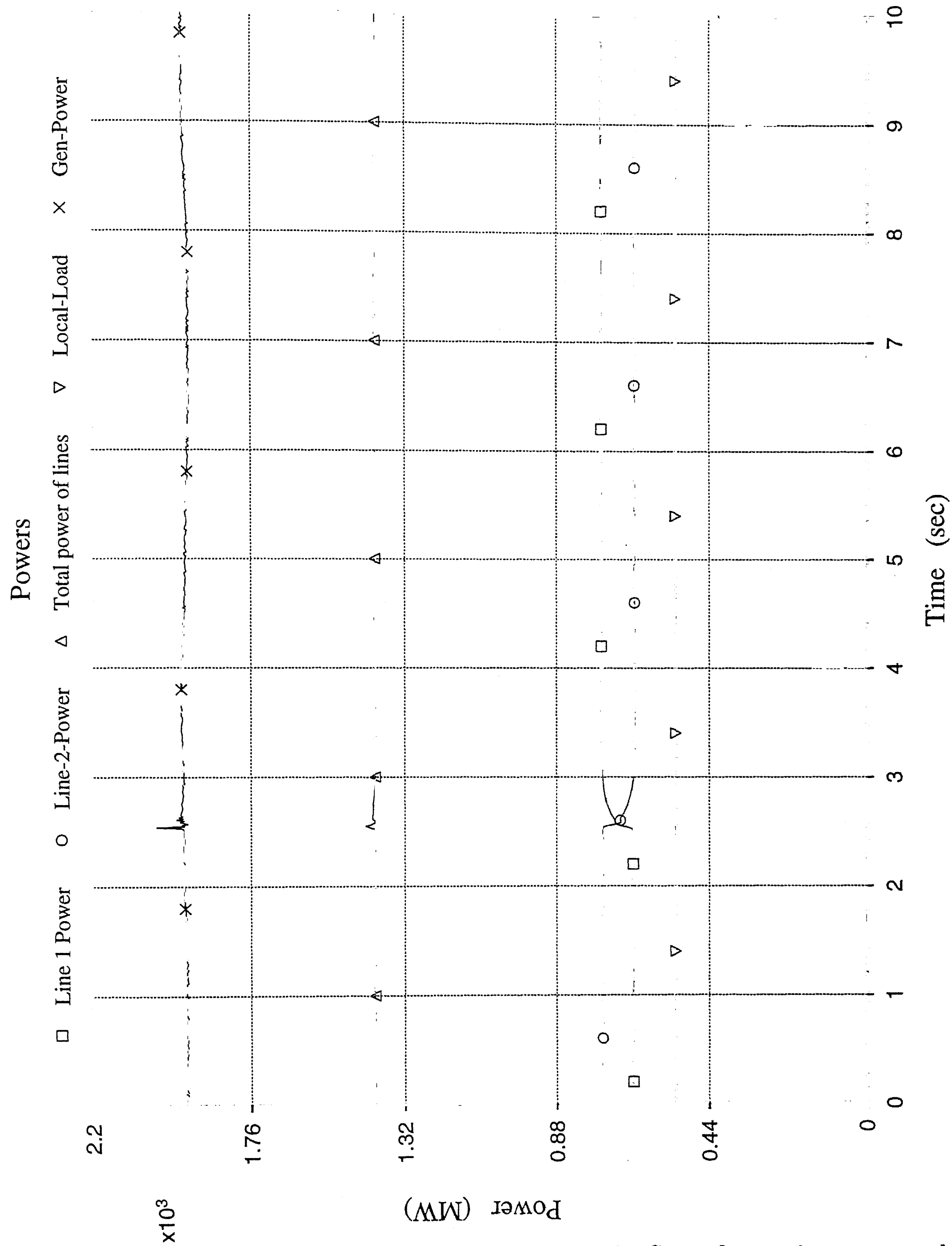

Figure 3.8: Powers: Two TCSCs - With Local load - Step change in power order

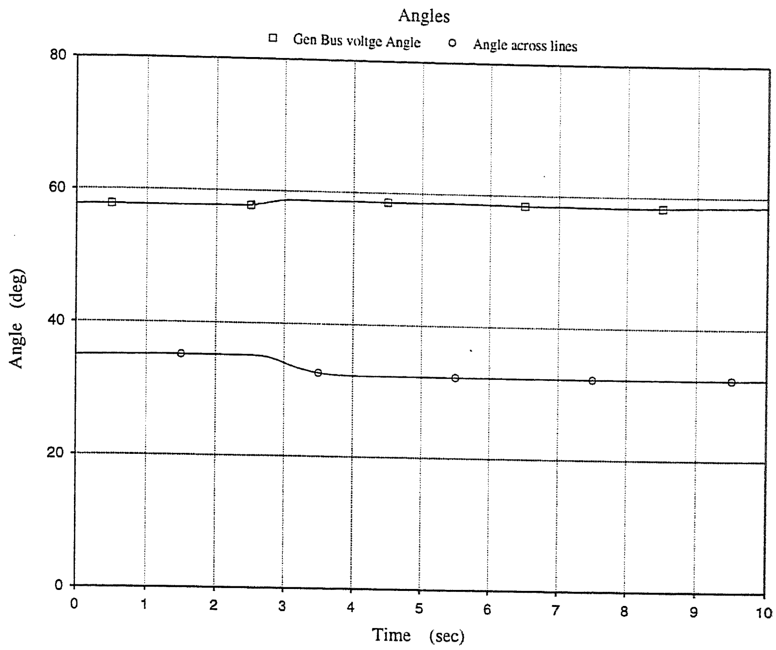

Figure 3.9: Angles: Two TCSCs - With Local load - Step change in power order

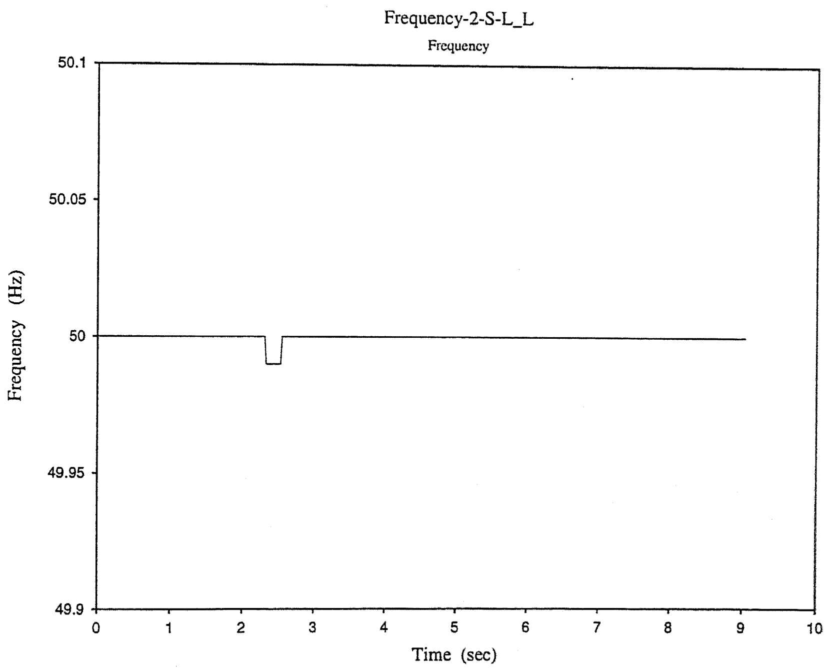

Figure 3.10: Frequency:Two TCSCs With Local load - Step change in power order

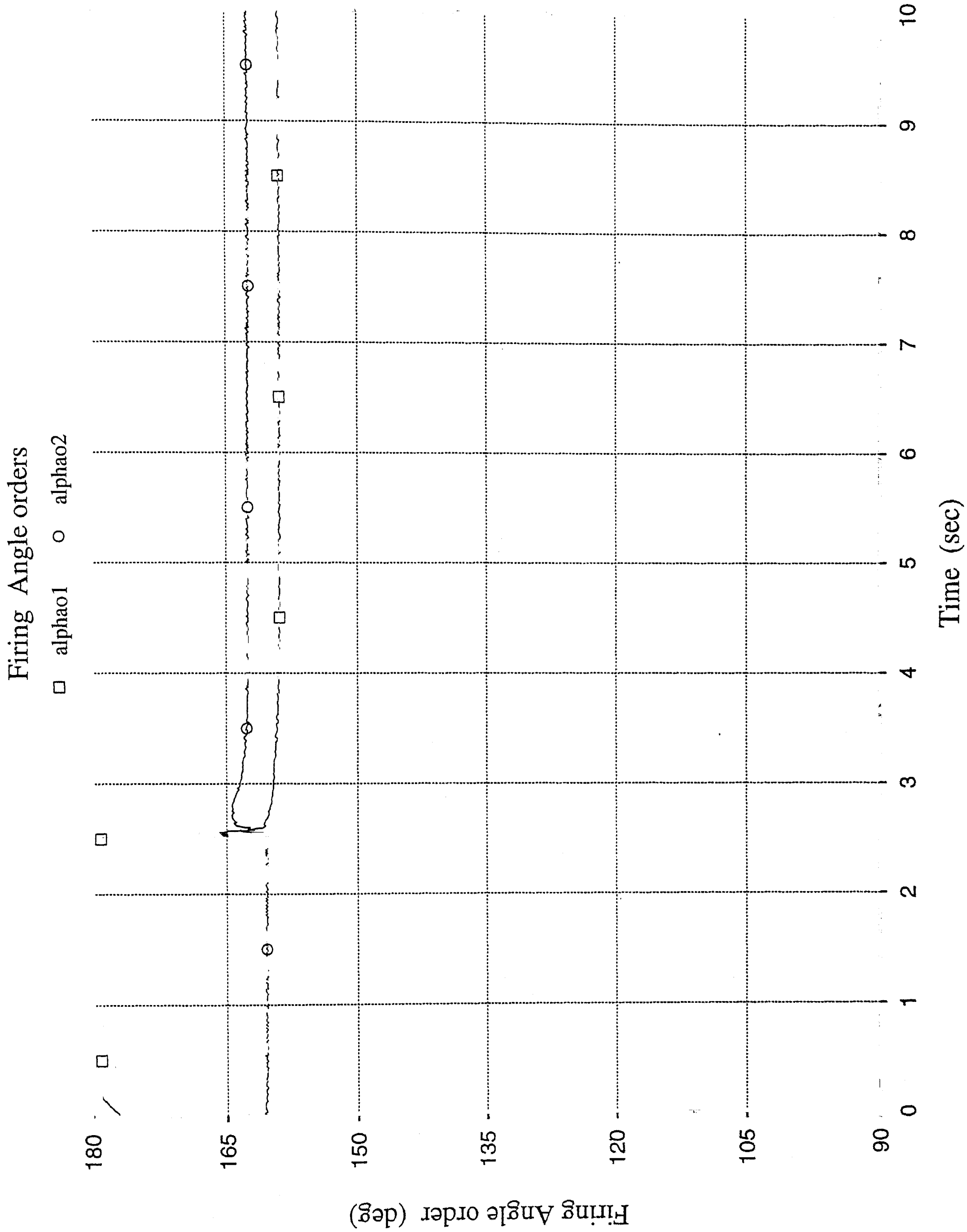

Figure 3.11: Firing Angles:Two TCSCs With Local load - Step change in power order

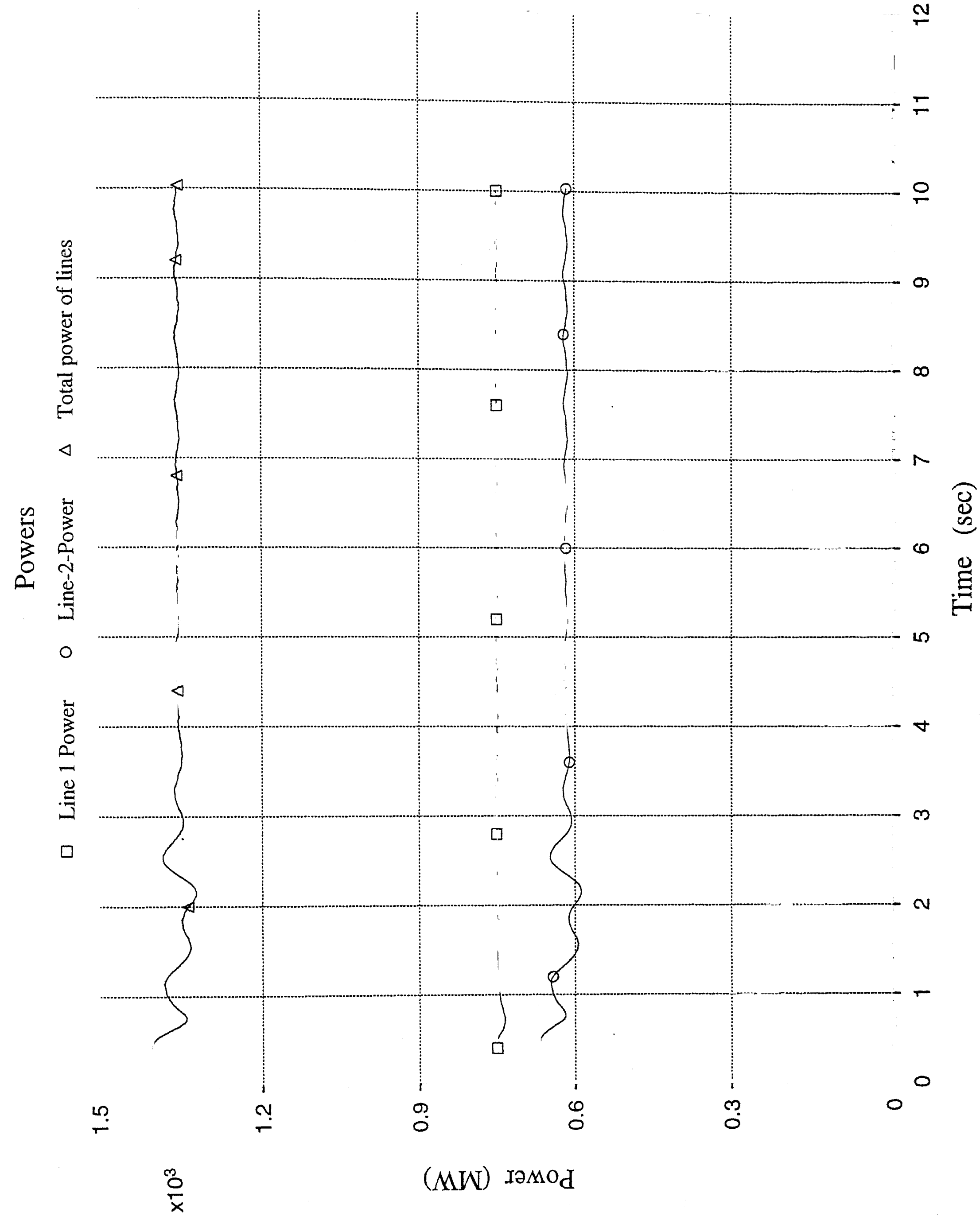

Figure 3.12: Powers: For reference change in Angle across lines

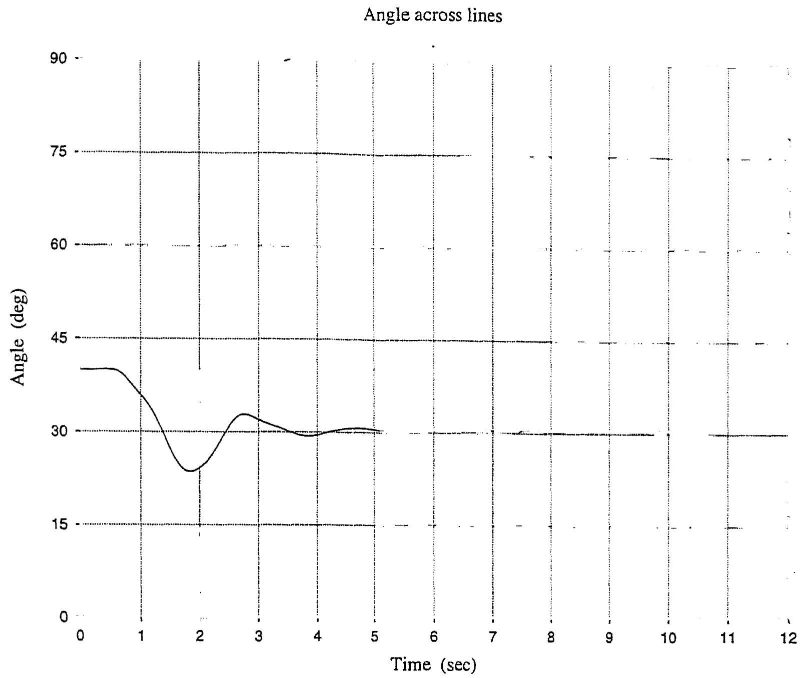

Figure 3.13: Angle Across Lines: For reference change in Angle across lines

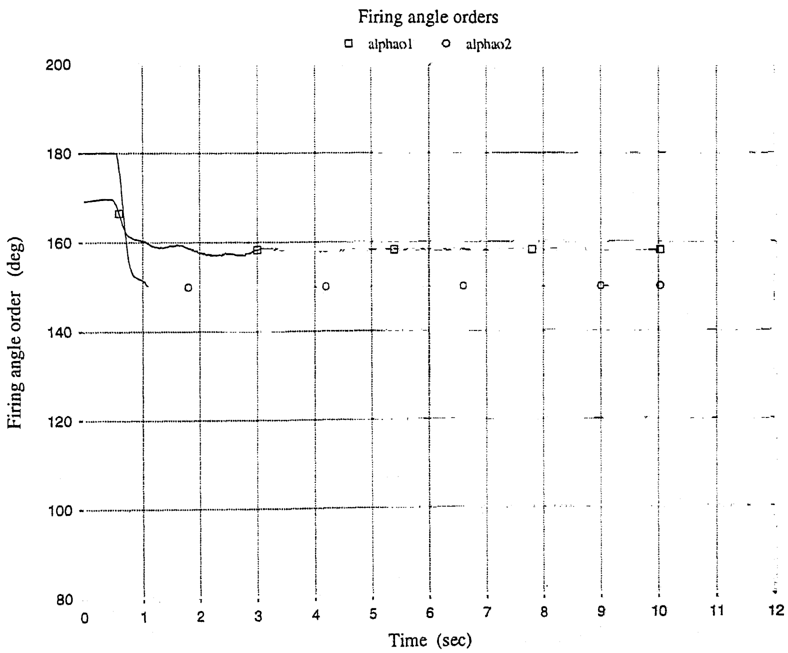

Figure 3.14: Firing Angles: For reference change in Angle across lines

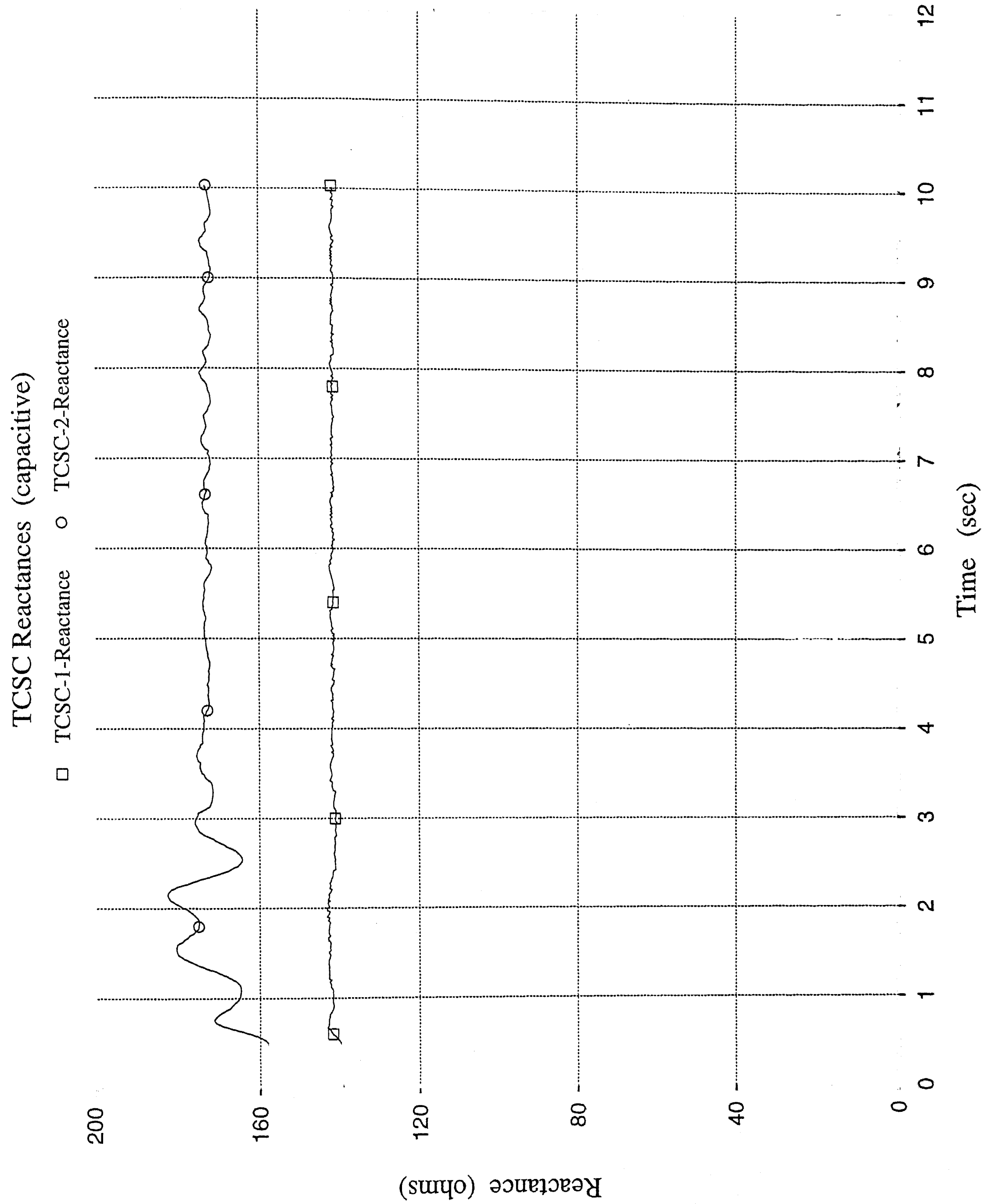

Figure 3.15: TCSC Reactances: For reference change in Angle across lines

3.1.4 Case 4:TCSC on both lines; no local load; response to transient fault

Here the results of a fault case considered are presented. A 3-phase to ground fault is created at the receiving end of transmission line 1 for a duration of 2.5 cycles at 3.0s. The prefault power flows 750MW and 650MW on lines 1 and 2. We observe the following salient features of the responses.

1. From Fig 3.16, it is seen that power on line-1 decreases from 750MW to 660MW initially. But, the power controller behaves in such a manner that line reactance reduces to boost the power. Finally, after the fault is removed, line-1 power regains its prefault value of 750MW.

2. Power on line-2 also decreases from 650MW to about 355MW initially. Then it reaches a maximum value of about 950MW before finally settling down to 650MW.

3. Generator power falls to 1200MW from 1400MW initially and then increases to 1550MW due to action of TCSC controllers and finally, it also settles to its prefault value of 1400MW after fault removal.

4. Angle across lines increases from 35^o to 36^o, then because of line 2 controller action, it falls to 33^o and finally settles to 35^o, (Fig3.17).

6. Frequency increases from 50Hz to 50.0704Hz, decreases to 49.9805 and then settles to 50H, (Fig3.18).

7. Terminal voltage of generator falls from steady state value of 1.05pu to 0.655pu, then goes to 1.05pu, (Fig3.20).

Fig 3.19 shows how the firing angles of TCSCs vary for this fault case.

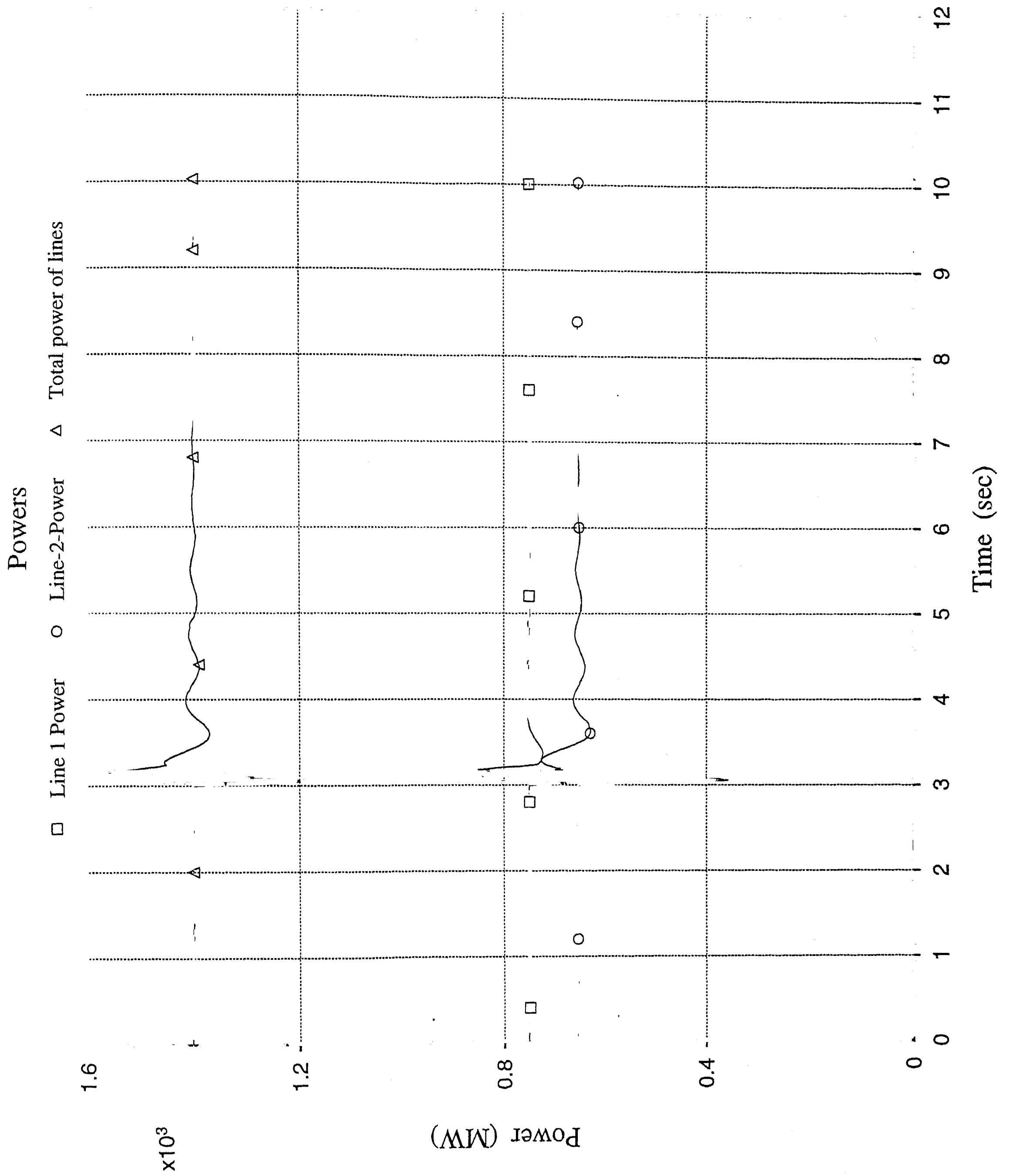

Figure 3.16: Powers: Two TCSCs 2.5 cycle Fault

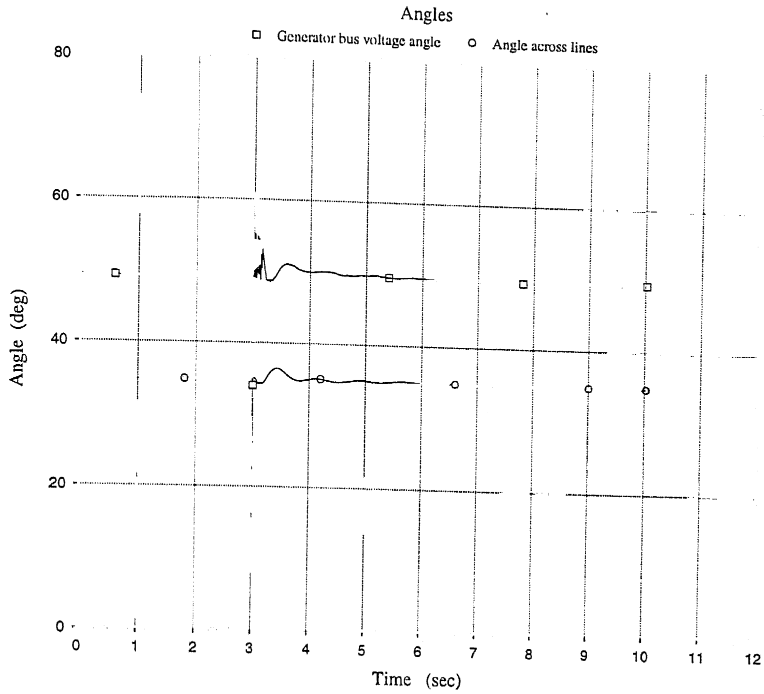

Figure 3.17: Angles: Two TCSCs 2.5 cycle Fault

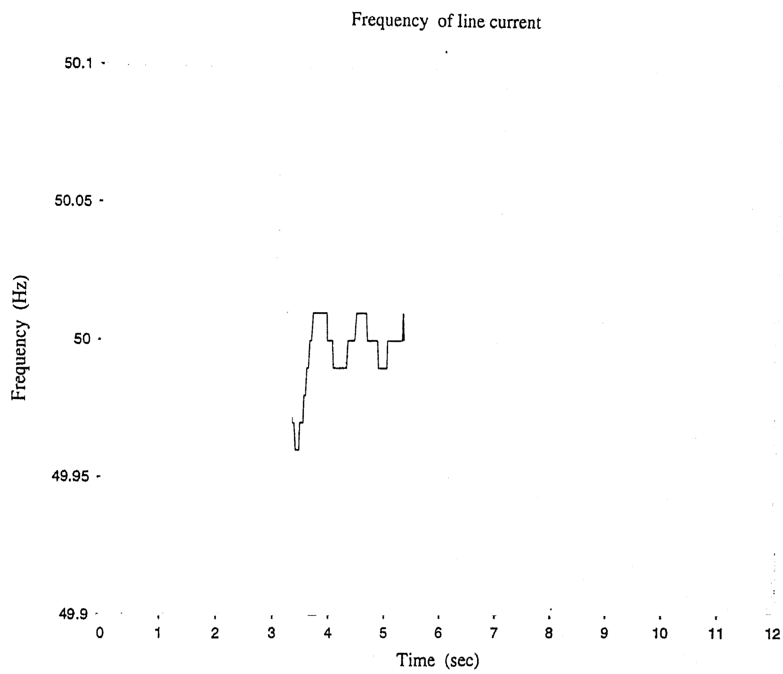

Figure 3.18: Frequency: Two TCSCs 2.5 cycle Fault

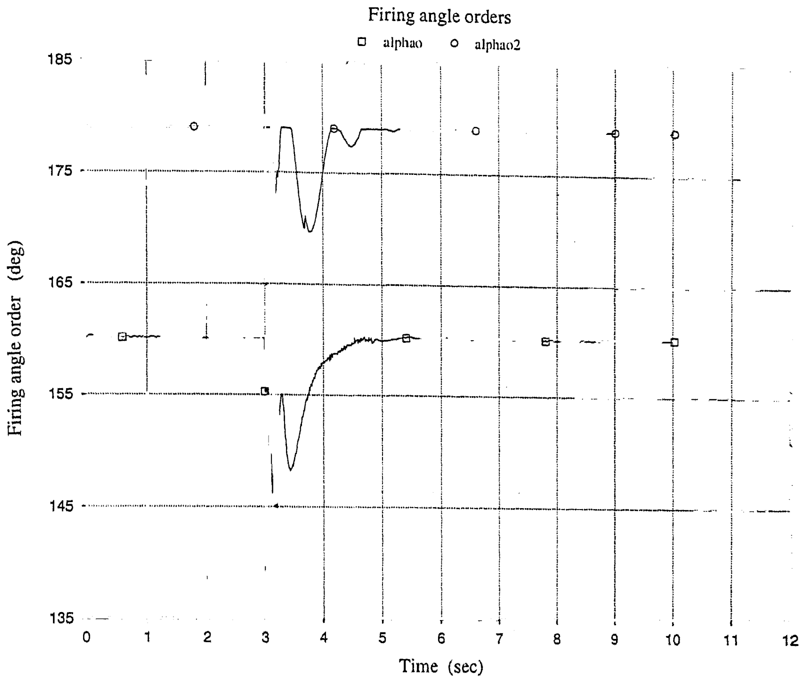

Figure 3.19: Firing Angles: Two TCSCs 2.5 cycle Fault

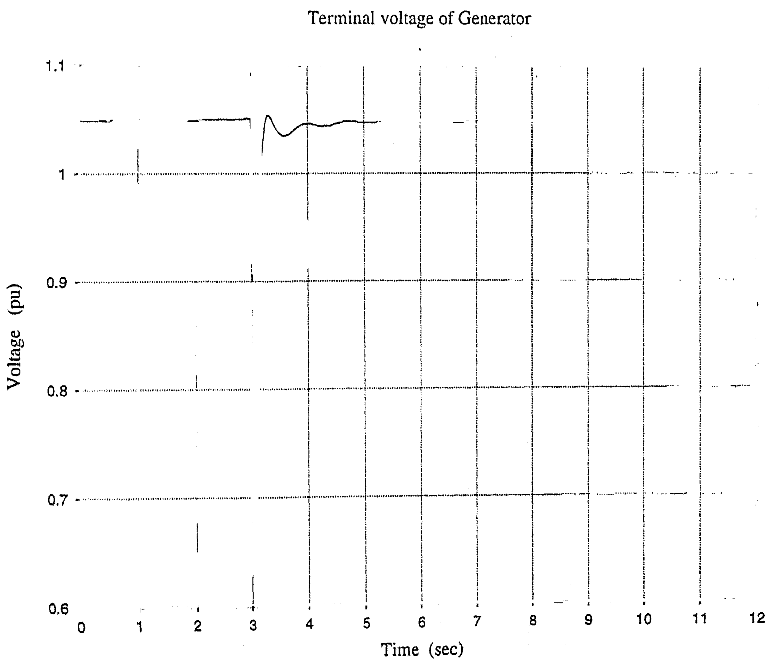

Figure 3.20: Generator terminal Volatge 2.5 cycle Fault With Two TCSCs

3.1.5 Case 5: Fixed compensation on both lines; no local load; response to transient fault

This case is considered to demonstrate the behaviour of system for the same fault as considered above, but without controllers. Each line has 20% fixed series compensation. 3-phase to ground fault is applied at the receiving end of transmission line-1 for a duration of 2.5 cycles at 3.0s. Figures 3.21-3.23 indicate responses in line and generator powers, generator terminal voltage angle and frequency of line current. Due to the fall in generator power, there is acceleration of generator as indicated by continuous increase in frequency. Loss of synchronism occurs. This shows that, the TCSC controllers not only increase the power transfer capability of lines but also improve the transient stability of the system significantly.

3.1.6 Case 6: TCSC on both lines; no local load; response to 5 cycle transient fault

This case demonstrates a 5 cycle fault. 3-phase to ground fault is applied at the receiving end of transmission line-1 for a duration of 5 cycles at 2s. Under prefault conditions each line carres 700MW of power. Even for this severe fault, the system remains stable due to action of TCSC controllers. Following observations are made from Figs 3.24-3.28.

1. Fig 3.24 shows that power on both lines fall down rapidly following the occurence of fault, the power levels are returned in a short time, within about 1.5s after removal of fault.

2. In the process of boosting the powers, it is seen that for a short time power levels reach higher than operating values, as much as 30% higher for line2 and for 15% for generator.

3. Fig 3.25 shows that angle across lines increases from prefault value of 35^o to as high as 37^o. However, because of controller action on second line, it reduces to 15^o and finally settles at 35^o.

4. Generator bus voltage angle increases from 50^o to 92^o, and then reduces to 33^o. Finally, it settles at 50^o.

5. Fig 3.26 shows that frequency increases to 50.2Hz, reduces to 49.9Hz and setlles at 50Hz finally.

6. Fig 3.27 shows how the firing angles of TCSCs vary to maintain power on line 1 and angle across lines. Fig 3.28 gives the voltage variation due to fault.

In case of such severe faults, power flow reduces drastically in a very small time. Hence, the controllers should not only be fast but also should have capability to boost the power to higher levels in order to reduce the accelerating power of generator. TCSC **L** and **C** should be so chosen that, without entering into resonance zone, the capacitive reactance should be sufficiently high to boost the power to required levels. Otherwise, the controllers will hit the lower limits, will not be able to boost the power to adequate levels and will fail to maintain system stability.

For all the cases considered, the simulation has been done using (Power System Computer Aided Design) PSCAD/EMTDC package. This package has been developed by HVDC Research Centre of Manitoba, Canada. It is a modified and graphical version of their earlier 'EMTDC' package. This is a time-domain simulation in a-b-c- frame of reference instead of d-q-o frame. The integration time-step taken is $15\mu s$. PSCAD can be used for extensive time-domain simulation of systems for both transient and small signal analyses. Synchronous machine models upto 7th order can be used. Switching circuits as well control systems can also be incorporated very easily. This makes the study easy and realistic. Machines, loads, transformers, transmission lines, cables, HVDC controls, thyristor controlled devices, measurement devices etc are all available readily in PSCAD. This package is being increasingly used by professionals.

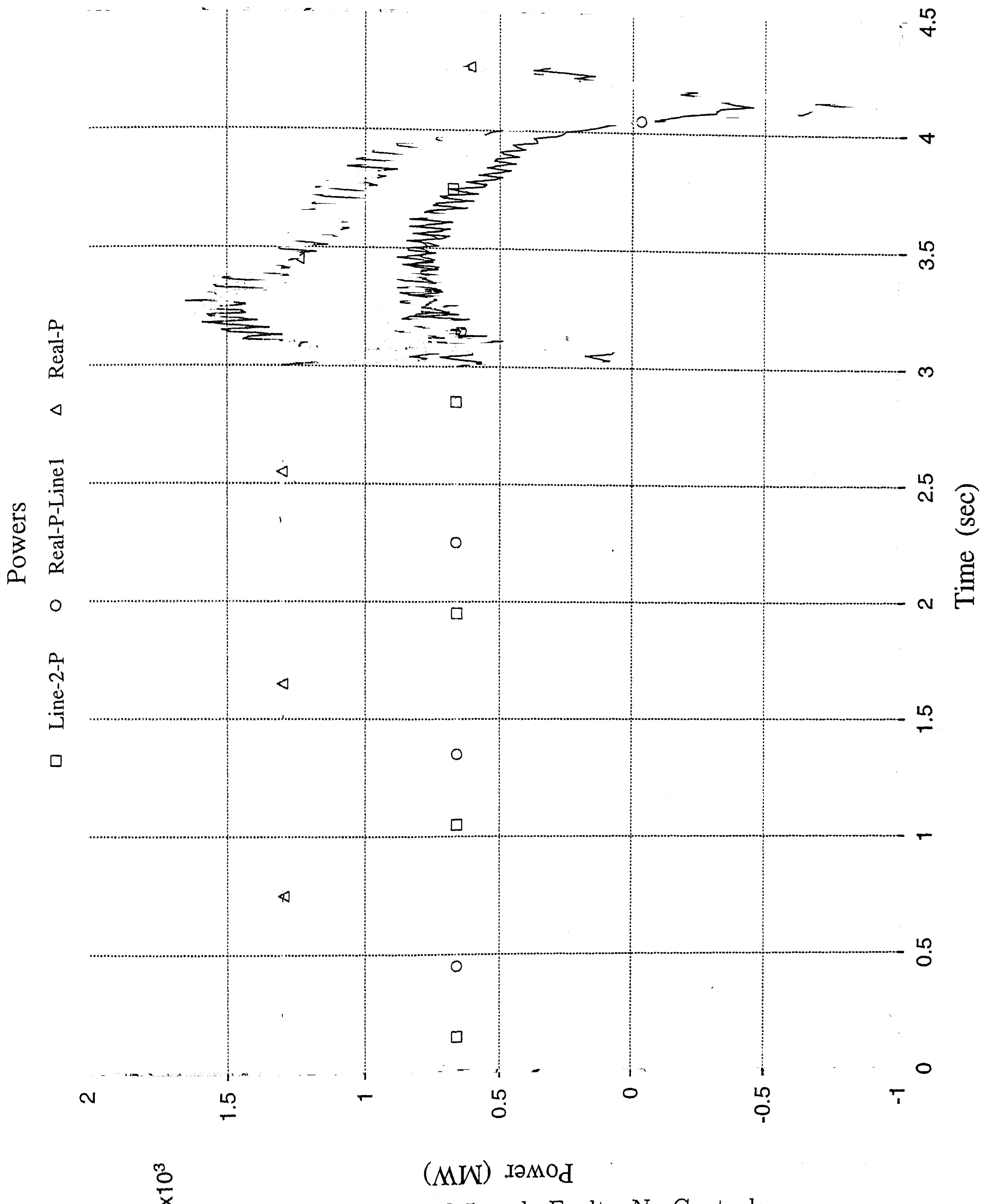

Figure 3.21: Powers: 2.5 cycle Fault - No Controls

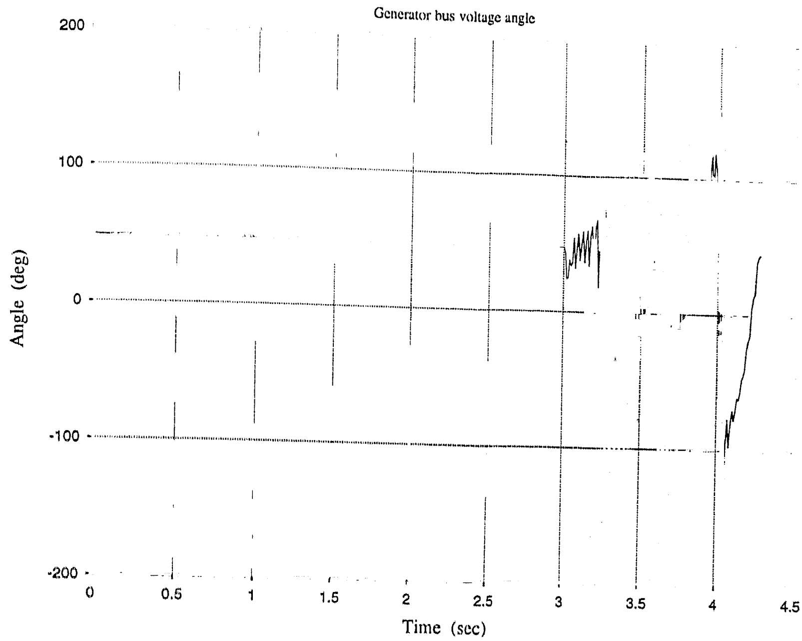

Figure 3.22: Generator Angle: 2.5 cycle Fault - No Controls

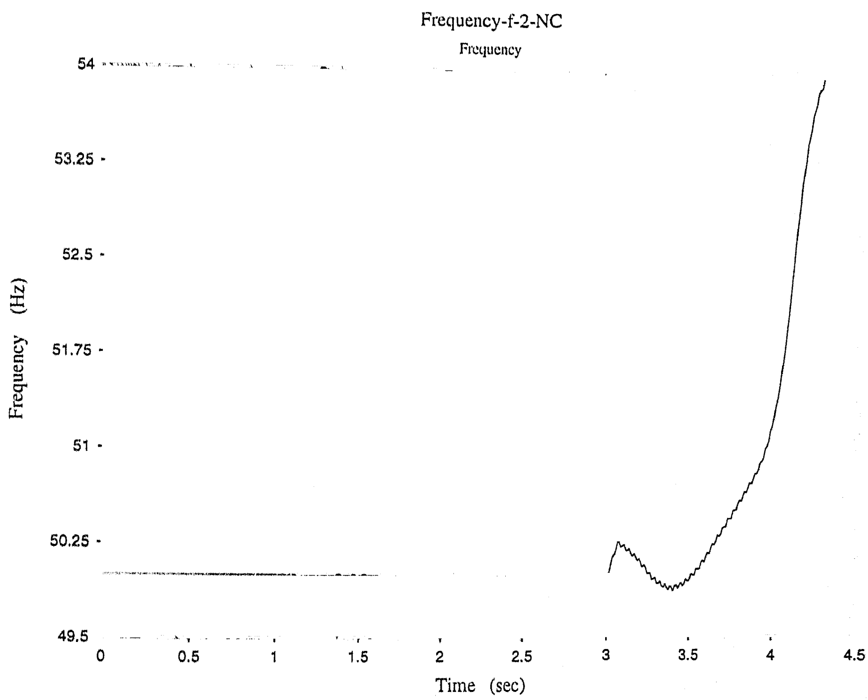

Figure 3.23: Frequency: 2.5 cycle Fault - No Controls

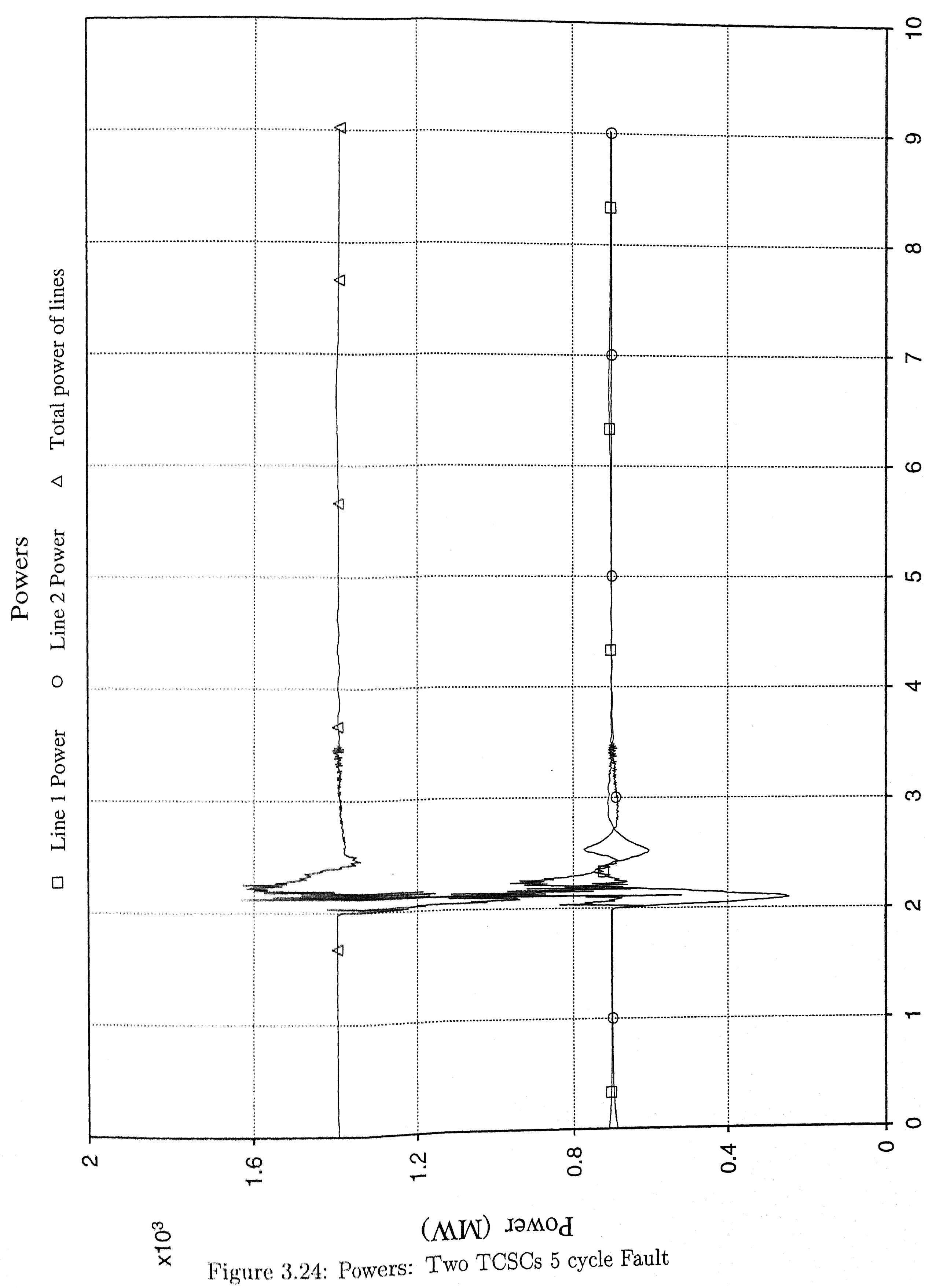

Figure 3.24: Powers: Two TCSCs 5 cycle Fault

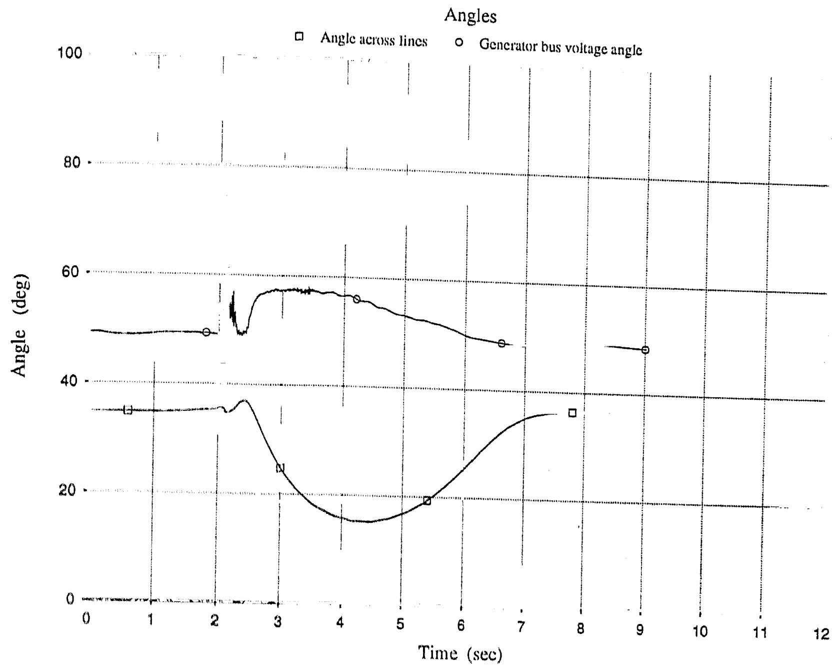

Figure 3.25: Angles: Two TCSCs 5 cycle Fault

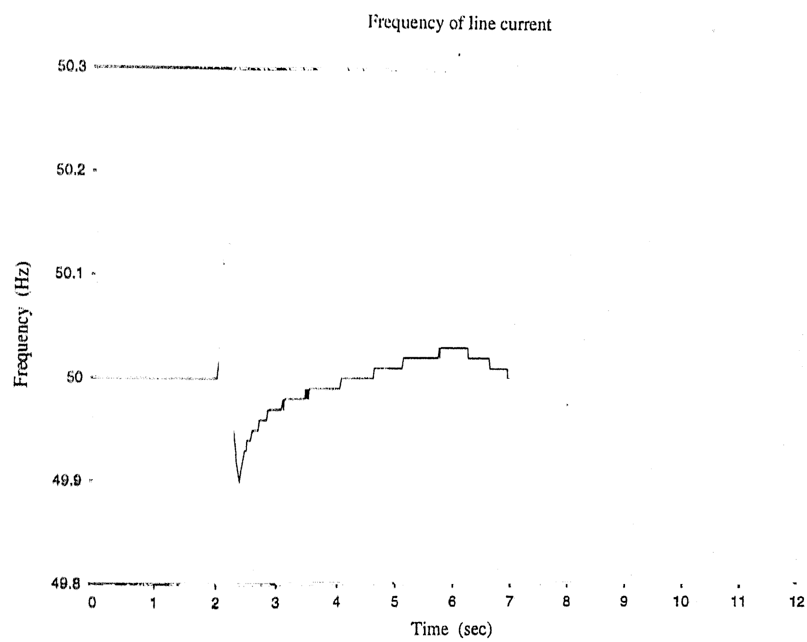

Figure 3.26: Frequency: Two TCSCs 5 cycle Fault

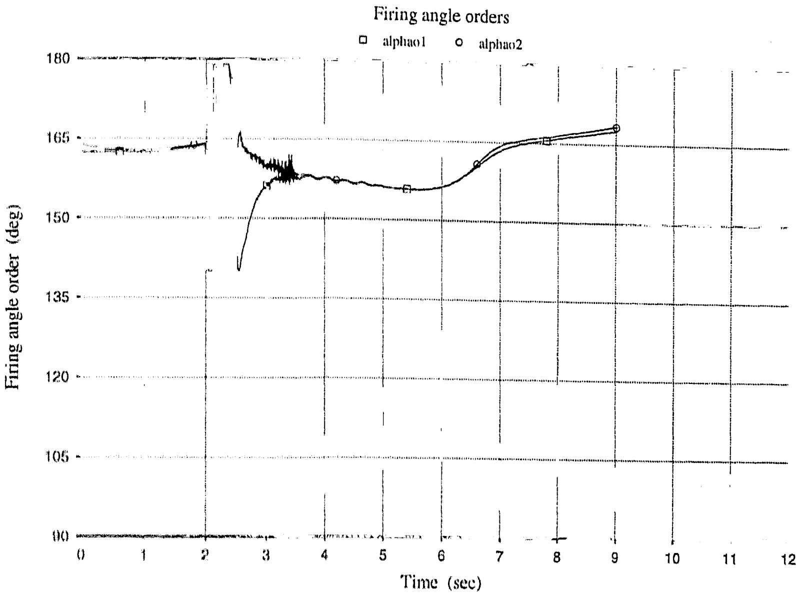

Figure 3.27: Firing Angles: Two TCSCs 5 cycle Fault

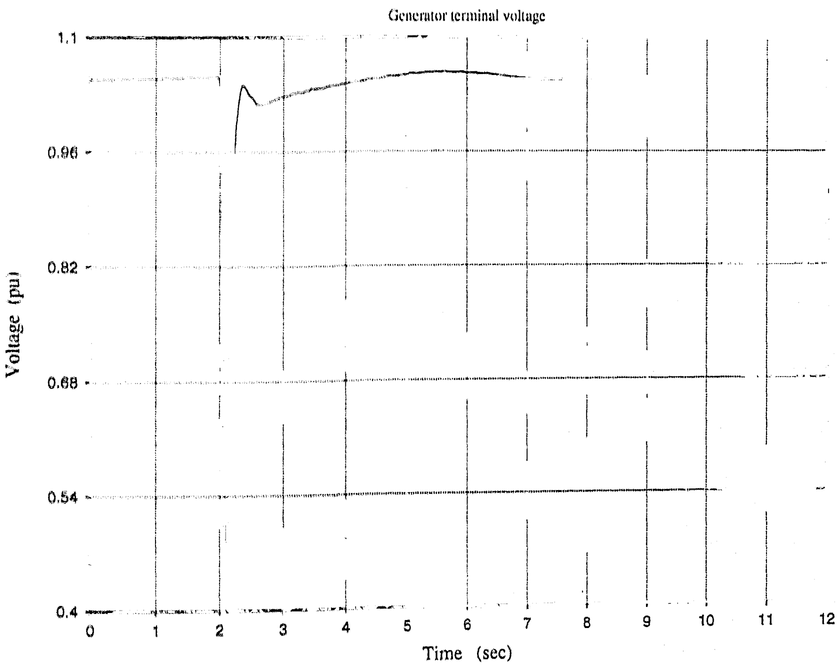

Figure 3.28: Generator terminal Voltage: 5 cycle Fault

3.2 Control System

TCSC control system comprises of

1. Thyristor firing control.

2. Power control (P-I control).

3.2.1 Firing Control

Operation of TCSC introduces harmonics in system voltages and currents. Therefore, both voltage across capacitor as well as current through TCR contain harmonics. Hence, it will be very difficult to give appropriate firing pulses with respect to these quantities. Therefore, while measuring either voltage across capacitor or current through TCR for reference purpose, they should be filtered to get sinusoidal wave-form for best detection of zero crossing instant. In all the earlier mentioned cases, voltage across capacitor is taken as reference. The advantage of this is that, firing strategy will be simple in the sense that, range of firing angle always lies between 90^o to 180^o. From 90^o to about 120^o, TCSC operates in inductive zone and above that upto 180^o, it operates in capacitive zone. Whereas if inductor current is used as reference, then the firing angle range should be between 0^o to something around 45^o in inductive zone and in capacitive zone, i.e. after some 50^o additional phase-shift of 180^o has to be added.

The voltages measured are passed through narrow band-pass filters with centre frequency of 50Hz. The filtered voltages are passed through a Phase-Locked-Loop (PLL), to produce a ramp corresponding to zero crossings. The proportional and integral gains of PLL are made high to track the frequency. This ramp output of PLL is compared with firing angle order given by P-I controller. The output of comparator gives firing pulse which lasts till 180^o, which is not necessary. Therefore, a similar pulse is generated with a 45^o delay with respect to first one and it is subtracted from first one to get a firing pulse of duration 45^o. The proportional gain of PLL is 500 and integral gain is 5000. It has been observed that individual phase firing scheme is better than equi-distant pulse firing scheme. Therefore, in

all the cases considered, individual phase firing scheme is used.

3.2.2 P-I Power Controller

Since both the TCSCs use P-I power controllers and the two transmission lines are identical, the P-I controllers are also made identical. For increasing power flow, as reactance has to be reduced for which firing angle has to be reduced, $\mathbf{P}_{meas}$-$\mathbf{P}_{ref}$ should be taken as error. This error is given to a P-I controller. $\mathbf{P}_{meas}$ and $\mathbf{P}_{ref}$ are in pu. For controller action to be fast, high gains are taken. In all the cases, proportional gain 300 and integrator gain of 2000 (integrator time-constant is 0.0005s) were used. These high gains are required particularly during transient faults. The P-I controllers of both the TCSCs have limiters which limit the output. The limits are 155^0 and 180^o for all cases, except for 5 cycle fault case, where they are 140^o and 180^o. The reason is that for 5 cycle fault case, the powers on both the lines reduce so much that, in order to boost to reasonable level to decelerate the generator 140^o lower limit was considered desirable. In the cases considered, there is no need for TCSC to go into inductive zone of operation. Therefore, the lower limits are kept at 155^o and 140^o as stated above.

Chapter 4

Conclusions

Long ac transmission lines are in general under-utilised because of inadequate compensation, limitation on line power angle imposed by requirement of transient stability margin and voltage limit For better utilisation of line capabilities, proper series compensation is imperative. Dynamic/variable series compensation has become the best choice for this purpose when compared with fixed compensation for achieving flexibility and also stable and safe operation. These controllers also improve transient stability. Independent operation of these controllers result in unwanted disturbances in unregulated lines Therefore, there is need for co-ordination of these controllers. In case of parallel lines having thyristor controlled series compensators. it is not possible to control power on both the lines independently. Under such situations, advantage can be taken by operating one of the TCSCs under angle control mode with the other in power control mode.

This thesis presented a novel way of controlling two parallel ac lines with TCSC on them and results of detailed PSCAD study of the proposed method presented.

The advantage of this method is that, with power controlling TCSC, desired power levels can be obtained. The second TCSC on the other hand not only allows rest of the power to flow through second line without any oscillations but also controls the angle across the lines. The control strategy is seen to be fast and effective. This control strategy not only enhances the power transfer capability of transmission lines but also improves the transient stability of the system tremendously. The effectiveness of the proposed control strategy for improvement

of transient stability has been established by studying its efficacy for prevention of loss of synchronism for a severe transient 3-phase fault Therefore, it can be concluded that this control strategy not only guarantees co-ordinated operation but also improves the transient stability. Even if unusual orders of reference are given, the controllers operate at their limits but preventing hazards.

Scope for further work

This thesis has drawn attention to the need for coordinated control of multi TCSC compensated ac lines. An example of control of a double circuit line was considered. In the more general case, appropriate formulation of control objectives and development of control strategies for realization of the objectives are necessary. It is envisaged that many interesting problems will be encountered in this area and many useful results will emerge.

Appendix

System Data

Generator data

V_{base}=22 kV. $S_{3_{base}}$=1110 MVA. f=50Hz.

Inertia constant **H**=3.22s. Mechanical friction and windage loss = 0.04pu.

$\mathbf{R}_a$=0.0036 pu. $\mathbf{X}_a$=0.21 pu. $\mathbf{X}_d$=1.933 pu. $\mathbf{X}_d'$=0.467 pu

$\mathbf{X}_q$=1.743 pu. $\mathbf{X}_q'$=0.228 pu. $\mathbf{X}_d''$=0.312 pu. $\mathbf{X}_q''$=0.312 pu.

τ_{do}'=6.66s. τ_{do}''=0.032s. τ_{qo}'=0.85s. τ_{qo}''=0.057s.

Initial Conditions

V=1.05 pu. Generator terminal voltage angle δ=0.60789^c

Exciter data

Exciter-type : exci35

Line-Neutral $\mathbf{V}_{base}$=12.701759 kV,rms

Measured ac voltage time-constant=0.02s. Controller lead time constant=1.5s

Controller lag time constant=1.0s. Exciter time constant=0.02s.

Exciter gain=100, Maximum field voltge $\mathbf{E}_{max}$=5pu Minimum field voltage $\mathbf{E}_{min}$=-5pu. Reverse resistance=15000 pu.

Sending end transformer data

22kV/500kV, 1110MVA. Y/Y Leakage Reactance=0.2 pu.

Transmission line data

Line length=400 miles. 500kV 1110MVA

Resistance=0.05 Ω/mile.

Inductive reactance=0.50675 Ω/mile.

Capacitive susceptance=8.108x10^6 Siemens-mile

L and C values of TCSC

L=0.0152H. This is spilt into two parts.

C=53 μF.

Receiving end transformer data

500kV/230kV Y/Y 1110MVA

Leakage Reactance=0.2 pu.

Infinite Bus voltage is 230kV

Bibliography

[1] "FACTS OVERVIEW", *CIGRE & IEEE Power Engineering Society April 1995*

[2] T.J.E. Miller, "Reactice Power Control in Electric Systems", *John Wiley and Sons, New York,* 1982

[3] E.Larsen, C. Bowler, B. Damsky, S. Nilsson, "Benefits of Thyristor Controlled Series Compensation", *CIGRE Session 1992, 5 Sept*

[4] P.S. Dolan, J.R. Smith and W.A. Mittelstadt, "A Study of TCSC Optimal Damping Control Parameters for Different Operating Conditions", *IEEE Transactions on Power Systems, Vol. 10, No. 4, Nov 1995*

[5] S. Nyati, C.A. Wegner, R.W. Delmerico, R.J. Piwko and D.H. Baker , "Effectiveness of Thyristor Controlled Series Capacitor In Enhancing Power System Dynamics: An Analog Simulator Study", *IEEE Transactions on Power Delivery , Vol. 9, No. 2, April 1994*

[6] K. Clark, B. Fardanesh, R. Adapa, "Thyristor Controlled Series Compensation Application Study- Control Interaction Considerations", *IEEE Trasactions on Power Delivery Vol. 10, No. 2, April 1995*

[7] Sudhir V. Bhat, "Investigations Into Control Strategies of Variable Series Compensation of Transmission Line", *M. Tech Thesis, IIT Kanpur, May, 1995.*

[8] Scott.G.Helbing and Karady, "Investigations of an Advanced form of series compensation", *IEEE Transactions on Power Delivery Vol.9, No.2, April 1994*